Bulletin
of
The Geological Society of America

VOLUME 57 February 1946 NUMBER 2

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Subscription, $10 per year.

Publication Office: Mt. Royal and Guilford Aves., Baltimore 2, Md.

Communications for publication should be addressed to The Geological Society of America, Dr. H. R. Aldrich, Secretary, 419 West 117th Street, New York 27, N. Y.

NOTICE.—Four weeks notice of change of address is necessary. In accordance with the rules established by the Council, claims for non-receipt of the preceding number of the Bulletin must be sent to the Secretary of the Society within three months of the date of the receipt of this number in order to be filled gratis.

Entered as second-class matter in the Post-Office at Baltimore, Md., under the Act of Congress of July 16, 1894.

Accepted for mailing at special rate of postage provided for in Section 1103 Act of October 3, 1917, authorized on July 8, 1918.

PAPERS IN PRESS FOR FORTHCOMING ISSUES

GEOLOGY OF A PART OF THE LOWER CONCHOS VALLEY, CHIHUAHUA, MEXICO. By Robert E. King and W. S. Adkins

IGNEOUS AND METAMORPHIC ROCKS OF THE SOUTHWESTERN PART OF THE RAMONA QUADRANGLE, SAN DIEGO COUNTY, CALIFORNIA. By Richard Merriam

GEOLOGY OF THE MT. WASHINGTON QUADRANGLE, NEW HAMPSHIRE. By M. P. Billings, *et al.*

TERTIARY AND QUATERNARY GEOLOGY OF THE LOWER PUERCO AREA, NEW MEXICO. By H. E. Wright, Jr.

OFFICAL AND STRATEGIC ANNOUNCEMENTS

Editoral Note.—The need for a means promptly to present material such as the following has long been felt, and the feasibility of using a few pages in each issue of the Bulletin is being studied by the Committee on Publications for recommendation and action by the Council in April.

Because much of the material is of short-lived interest, these pages will not be numbered and can easily be removed before binding the volume. Material believed suitable for this section should be sent to Dr. H. R. Aldrich, Secretary, Geological Society of America, 419 West 117 Street, New York, N. Y. For any particular issue contributions should reach us no later than the tenth of the preceding month.

VETERANS' RETRAINING PROGRAM IN GEOLOGY*

By W. H. Bradley

Chief Geologist, U. S. Geological Survey, Washington, D. C.

During the past five years it is estimated that the armed forces absorbed some fifteen hundred young American geologists of graduate, near-graduate, or post-graduate status, only a small number of whom had gained any experience in professional application of their learning.

During their terms in the armed services few of these young men have had the opportunity of using their geological training or of acquiring additional geologic knowledge. It may therefore be assumed that they have suffered considerable loss of geologic skill and knowledge and are thus not prepared to resume their studies or professional activities in competition with those geologists whose careers have not been interrupted by the war.

Because of this situation and the current demand for trained geologists, the U. S. Geological Survey proposes to undertake a program of training in the form of supervised field, laboratory, and office work that will enable discharged veterans to adjust themselves more quickly and with more confidence in resuming their careers. The Survey proposes to undertake only this applied phase of the retraining. It recognizes that many of the expected trainees will require preliminary academic courses in college or university geology departments that are equipped to give concentrated courses of graduate calibre.

The proposed dual program has been discussed with heads of the geology departments of the Universities of Chicago, Columbia, Harvard, Johns Hopkins, Princeton, and Yale; and they have indicated their approval of the plan in principle. Heads of geology departments in other schools interested in participating in this phase of the program may obtain pertinent information from the heads of the geology departments of those universities. Further information concerning the Geological Survey's phase of the program may be obtained by writing to W. H. Bradley, Chief Geologist, Geological Survey, Washington 25, D. C.

The instruction of qualified veterans in participating schools will, insofar as is feasible, be adjusted to the specific needs and interests of the individual to better equip him to undertake and benefit by Survey or other professional experience in field, laboratory, and office work during the 1946 field season.

Candidates for these temporary appointments to the Geological Survey will be selected on a competitive basis through the channels of the Civil Service Commission, and in accord with veterans' preference policies. It is hoped, however, that veterans who apply will have had the benefit of the preparatory college or university retraining before they seek appointment.

The number of veterans which the Survey will be able to absorb will depend upon the amount of funds appropriated to the Survey for geologic investigations. An estimate of the size of the field program should be available by spring after the House reports out the appropriation bill. As many as possible of the most competent temporary appointees will be given the opportunity of accepting more permanent appointments on the Geological Survey staff, or will be given aid in obtaining appointments in other governmental agencies or in industry.

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This dual program will operate on a very flexible basis, to take care of all individual cases, involving individuals whose academic training and professional experience to date lie within a rather wide range. It will be fitted also to individual desires, to allow for academic training only, for Survey experience only, or for both, depending on the qualifications and wishes of the individual.

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1946 ANNUAL MEETING

The Annual Meeting for 1946 will be held at The Stevens, Chicago, December 26–28. Chairman of Local Committee, J Harlen Bretz.

OFFICIAL CALENDAR

February 25–28	A. I. M. M. E. meeting, Palmer House, Chicago
March 15	Final spring date for filing applications for grants
March 27–30	A. A. A. S. meeting, St. Louis
April 1–4	A. A. P. G. meeting, The Stevens, Chicago
April 13	Meetings, committees on Publications and Projects, New York
April 19–20	Cordilleran Section meeting, University of California, Berkeley
April 27	Council meeting, New York

East Charlemont
Deerfield River
U.S. Hr. No. 2
East Otis Brook
Walnut Hill
1226
Cleason
North
Decl. 14½°
0
½
1
2
Scale in Miles
Mary Lyon Hill

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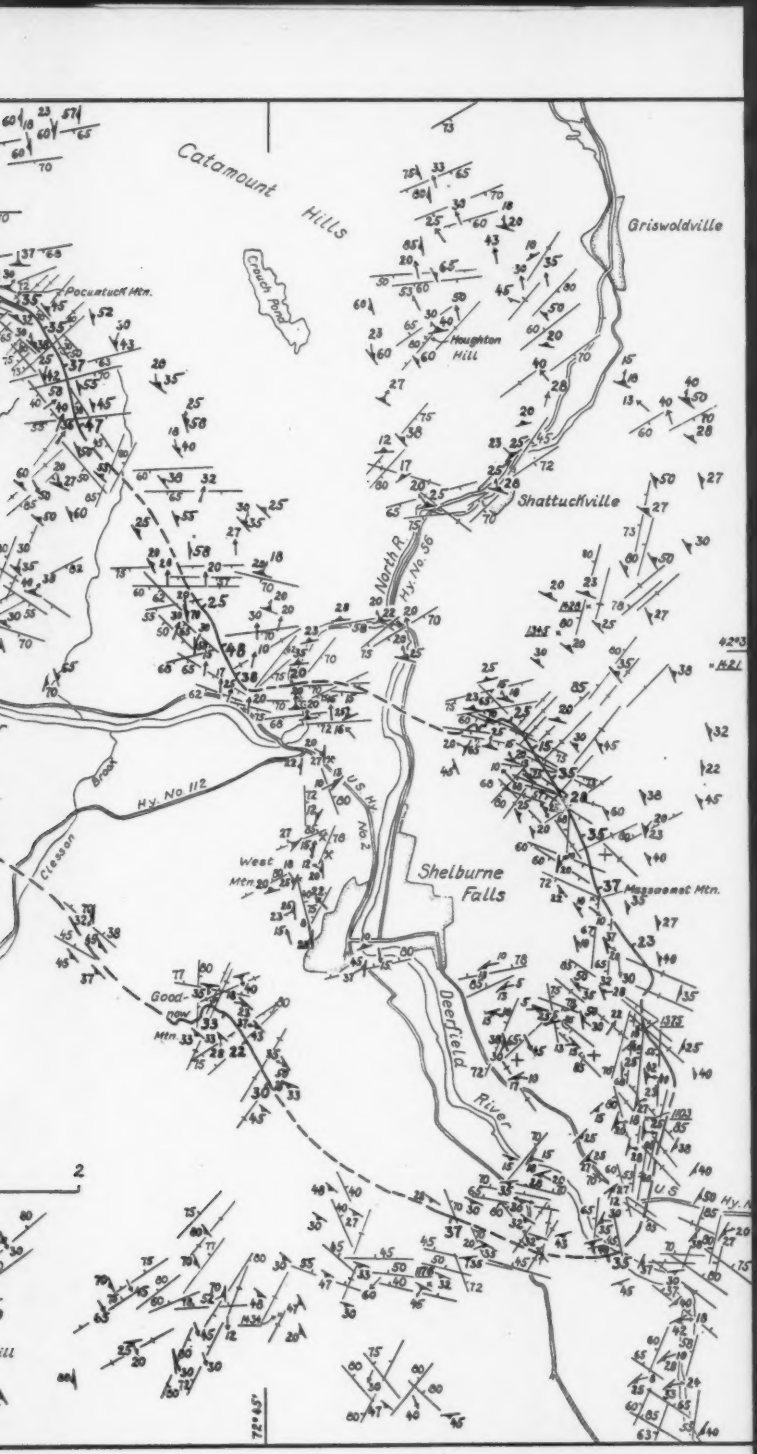
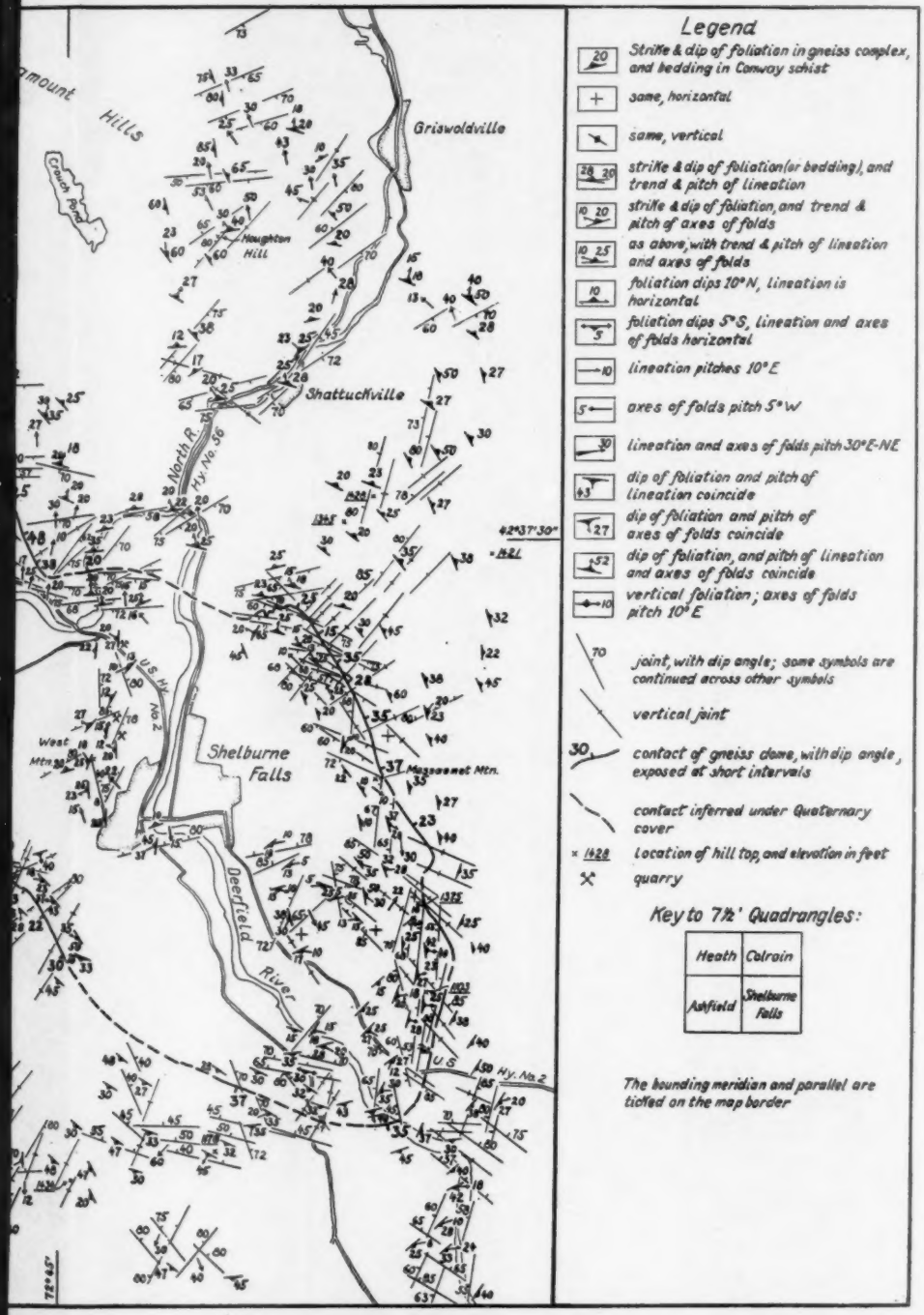


TRUCTURE MAP OF SHELBURNE FALLS GNEISS DOME, MASSAC


Legend
Strike & dip of foliation in gneiss complex, and bedding in Conway schist
same, horizontal
same, vertical
strike & dip of foliation (or bedding), and trend & pitch of lineation
strike & dip of foliation, and trend & pitch of axes of folds
as above, with trend & pitch of lineation and axes of folds
foliation dips 10° N, lineation is horizontal
foliation dips 5° S, lineation and axes of folds horizontal
lineation pitches 10° E
axes of folds pitch 5° W
lineation and axes of folds pitch 30° E-NE
dip of foliation and pitch of lineation coincide
dip of foliation and pitch of axes of folds coincide
dip of foliation, and pitch of lineation and axes of folds coincide
vertical foliation; axes of folds pitch 10° E
joint, with dip angle; some symbols are continued across other symbols
vertical joint
contact of gneiss dome, with dip angle, exposed at short intervals
contact inferred under Quaternary cover
location of hill top, and elevation in feet
quarry
Key to 7½' Quadrangles:
Heath
Colrain
Ashfield
Shelburne Falls
The bounding meridian and parallel are ticked on the map border
Griswoldville
Shattuckville
Shelburne Falls
Deerfield River
North R.
Hy. No. 56
U.S. Hy. No. 2
Mt. Massasoit
West Mtn.
Houghton Hill
Crouch Road
Hills
42°37'30"
72°45'

F SHELBURNE FALLS GNEISS DOME, MASSACHUSETTS

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 57, PP. 125-160, 7 PLS., 9 FIGS FEBRUARY 1946

GNEISS DOME AT SHELBURNE FALLS, MASSACHUSETTS

BY ROBERT BALK

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ABSTRACT

The Shelburne Falls gneiss dome, in the eastern Berkshire Hills of western Massachusetts, consists of amphibolitic metavolcanics, intruded by sills and complex *lit-par-lit* injection zones of a quartz diorite and its associated volatiles. The dome is surrounded by the Conway schist of early Paleozoic age. The principal rock types are described.

The dome surface dips outward at gentle angles, and the gneiss-schist contact is conformable, though an original unconformity is suggested in a few places. Sills or apophyses of quartz diorite in the schist are lacking. Neither the distribution of metacrysts nor the mineral composition and texture of the schist shows zoning with regard to the gneiss dome. It is concluded that the gneiss complex is older than the Conway schist, but that both the Conway schist and the gneiss have been silicified near the dome border, and chlorite, muscovite, tourmaline, and a few thin pegmatites have been introduced near this surface. It seems that these changes occurred during, or soon after, the metamorphism of the Conway sediments. At about the same time a few dikes of quartz diorite porphyry were intruded into the gneiss and the schist. At least 3 of them have been silicified, tourmalinized, and micacized.

Tightly compressed, isoclinally folded amphibolite tracts in the gneiss complex, with axes of folds and lineation in various directions, contrast with gently flexed or mildly folded Conway schist in the vicinity of the dome. Axes of folds and lineation pitch off the dome for the most part, though not everywhere in the steepest directions. Inward-dipping funnel joints near the dome border, and steep fractures radiating outward from it, attest to the mechanical expansion of the crust during the doming.

The association of amphibolitic metavolcanics with soda-rich igneous rocks, in the gneiss complex, resembles that of certain gneissic terranes in southeastern Vermont and southwestern New Hampshire more closely than the microcline-rich gneisses of the crest of the Berkshire Hills.

INTRODUCTION

SIGNIFICANCE OF THE AREA

The eastern slopes of the Berkshire Hills in Massachusetts are underlain by a thick series of crystalline schists that display a rather uniform easterly regional dip. Along the crest of the range—here called the Hoosac Range—they lean against pre-Cambrian granitic gneisses (Pumpelly, Wolff, and Dale, 1894). Emerson (1898a; 1898b)

studied the eastern schist formations and established a sequence from west to east, which has not been changed by subsequent work (Emerson, 1917, correlation chart, opp. p. 16). As there is no compelling evidence for repetition of schist members by faulting or folding, it may be assumed that the formations are progressively younger

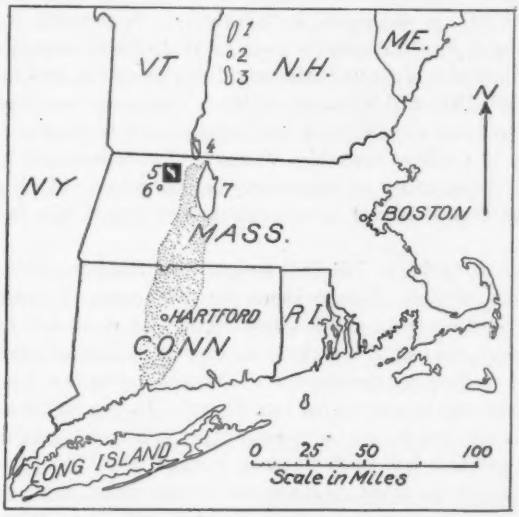

FIGURE 1.—*Index map of southern New England*

Showing location of Plate 1 (black square), Triassic lowland of Connecticut Valley (stippling), and locations of other gneiss domes. 1: Croydon dome, New Hampshire; 2, 3: Unity dome, New Hampshire; 4: Vernon dome, Vermont-New Hampshire; 5: Shelburne Falls dome; 6: Schist dome at Goshen, Massachusetts; 7: Pelham dome, Massachusetts.

from west to east. This agrees with the evidence afforded by the fossil locality near Bernardston, Massachusetts, at the extreme eastern base of the range, about 10½ miles northeast of Shelburne Falls (Emerson, 1898a, p. 253–299). Here a series of phyllites which contain a lens of fossiliferous marble appears to rest on the schists of the eastern foothills. The marble is thought to be Devonian (Balk, 1941), and thus the schists of the eastern Berkshire Hills in this portion of the State would seem to be of Cambro-Ordovician age, although they may include late pre-Cambrian phases at the extreme west, and Silurian rocks at the extreme east.

The regional easterly dip of the schists is interrupted at three places (Fig. 1), *viz.*: (1) In Vernon township, extreme southeastern Vermont, and Hinsdale township, extreme southwestern New Hampshire, a mass of gneiss and basic metavolcanics forms an oval uplift, 2 by 3 miles, with a north-south axis (unpublished field work by Balk); (2) The Shelburne Falls dome of gneissic quartz diorite and amphibolite, elongated in a SE.-NW. direction, with a maximum length of 6½ miles, and an average width of somewhat less than 2 miles; (3) A remarkable dome structure in mica schist, without a proven core of gneiss, near the village of Goshen, Massachusetts, 9 miles south-southwest of Shelburne Falls (Emerson, 1898a, p. 175–176).

Emerson (1898a, p. 38–41; 1917, p. 248–252) briefly described the Shelburne Falls area. Tentatively he correlated the gneiss with the Becket gneiss of the crest of the Berkshire Hills. This rock was first considered to be Cambrian, but later its pre-Cambrian age was recognized. In 1898, the Conway schist, which surrounds the gneiss, was assigned to the Silurian (Emerson, 1898a, p. 184, Pl. 34, legend). In 1917, Emerson (1917, p. 46) called it "Silurian?". Northward, in Vermont, the formation is probably identical with the so-called Waits River formation (Richardson, 1906, p. 86; for discussion of age and lithology of this formation, *see* Currier and Jahns, 1941, p. 1492, 1505–1506, and Wilmarth, 1938). The nearest outcrops of this formation, specifically referred to as Waits River limestone, are 12 miles north-northeast of Shelburne Falls, in Guilford township, Vermont (Richardson and Maynard, 1938, p. 92). Though the exact age of these nearly unfossiliferous rocks is extremely difficult to determine, Ordovician age agrees with the now known facts better than other ages.

In 1917, Emerson (1917, p. 248–253) assigned the Shelburne Falls gneiss to the late Carboniferous, without citing evidence for this change of interpretation. Although gneissic intrusive rocks of late Carboniferous age occur in central Massachusetts near Worcester, the intrusive rocks in the eastern Berkshire Hills call for detailed areal studies before their relationships to the various crystalline formations west of Connecticut River can be considered established. To the writer's knowledge, no such studies have been made, and the present paper is directed along this line. If the Shelburne Falls gneiss is late Carboniferous, it might show intrusive contacts with the Conway schist, or the schist, as it approaches the gneiss, might show significant changes in grade of metamorphism, coarseness, or other features, from which it could be inferred that the igneous component of the gneiss complex has caused the metamorphism of the argillaceous rocks. If the gneiss is of pre-Conway age, there might be a sedimentary contact, and conceivably even an unconformity, between the two formations. If the gneiss is late Paleozoic, some interesting conclusions could be drawn with regard to the distribution and composition of intrusive masses in this part of the New England mountains. If the gneiss is pre-Conway, it would represent an uplift of otherwise concealed basement rocks. This would permit some tentative, but nevertheless interesting, correlations with petrologically similar or dissimilar gneissic complexes in other directions.

In the writer's opinion, the various observations described in this paper point toward pre-Conway age of the gneiss complex, but whether it is of pre-Cambrian, or early Paleozoic, age is left undecided. The perfect dome structure resembles that of several domes in western Massachusetts (Fig. 1), and the writer suspects that additional domes may perhaps be brought to light, once the geology of southeastern Vermont is better known.

GENERAL DESCRIPTION OF THE AREA

The crest of the Hoosac Range lies 17 miles west of Shelburne Falls, and the summit elevations, near 2500 feet along the crest, decrease gradually eastward. Deerfield River, which drains this portion of the range, flows southward for about 12 miles in a steep-walled gorge which constitutes one of the most beautiful portions of

the Berkshire Hills. Near the village of Zoar, 10½ miles west-northwest of Shelburne Falls, the stream turns sharply to the east. Here the valley widens, and at the eastern end of this 7½-mile stretch, the river enters the Shelburne Falls dome and traverses it along its major axis (Pl. 1).

With the exception of a narrow, north-south trending ridge which causes a loop of the river to the north, the dome is a topographic basin, surmounted by an almost continuous escarpment of Conway schist. The river has breached the scarp on both ends of the dome; and, where the schist reappears southeast of the dome, the valley narrows again, although the slopes rise rarely more than 500 feet above the stream level. Eight miles southeast of the dome, Deerfield River enters the Connecticut River lowland.

The aforementioned ridge, called West Mountain, divides the gneiss dome topographically into two portions, and the floor of the northwestern one stands about 150 feet higher than the other. A long and precipitous scarp, on the east side of West Mountain, and a few scattered ledges provide the only outcrops within the dome, but the geologically more important contact zone is unusually well exposed in the escarpment that encircles the dome. Even where North River and other, smaller tributaries of the Deerfield enter the basin, outcrops are sufficiently numerous to permit accurate mapping of the dome contact. Where the escarpment rises higher, as at Massaemet Mountain (also known as Shelburne Mountain, 1588 feet) and Pocumtuck Mountain (1873 feet), the contact is excellently exposed in continuous cliffs and can be walked out for miles.

Shelburne Falls may be reached from Greenfield, or North Adams, Massachusetts, by U. S. highway no. 2 (the "Mohawk Trail"), or by railroad from the same towns (Pl. 1). A few roads that traverse the area are shown on Plate 1.

FIELD WORK AND ACKNOWLEDGMENTS

Field work in the area was begun in 1936, but was interrupted for several years. After the publication, in 1943, of excellent new topographic maps, about 4 weeks were spent in collecting specimens from significant outcrops, and tracing the various structural and petrologic features of the dome and its surroundings; 138 thin sections and 3 chemical analyses were prepared.

The writer is indebted to Dr. W. H. Bradley, Chief Geologist of the U. S. Geological Survey, for permission to use a blueprint copy of the new Heath, Massachusetts topographic quadrangle prior to publication. He is obliged to Mr. Lee C. Peck and Dr. Frank F. Grout for the preparation of three chemical analyses, and to Dr. Ernst Cloos for reading and criticizing the manuscript.

DESCRIPTION OF ROCKS

GNEISS COMPLEX

General Statement.—The gneiss complex of the dome consists of two phases, an amphibolite series, and a quartz diorite gneiss. The amphibolite series is the older and has been injected and "soaked" by the later quartz diorite. The penetration has reached various degrees. In some places, the quartz diorite forms distinct sills, as

much as 30 feet or more thick (Pl. 3, fig. 3), whereas in other exposures there are extensive *lit-par-lit* injection zones, hundreds of feet thick, in which no sharp boundaries between the two components can be drawn.

The mixed zones display remarkably intense folding. Emerson (1917, Pl. 9A, opp. p. 245) gives a good illustration, to which we have added a few (Fig. 2; Pl. 2, fig. 1). Entire ledges of Goodnow and West Mountain consist of myriads of small near-isoclinal folds and zigzags which follow so many directions that their measurement is very tedious. Plate 7 illustrates some of the variations seen in a small portion of a large ledge in Deerfield River at Shelburne Falls.

Perhaps the simplest structure of the dome is found in the northwesternmost section, where subhorizontal sills of quartz diorite near the center, are surrounded by gently outward-dipping layers near the contacts. Whether the southeastern portion of the dome has a correspondingly simple structure is not quite certain for want of exposures.

Amphibolite.—Typical exposures of amphibolite consist of thinly layered, grayish-green, medium- to fine-grained rocks that part at the blow of a hammer into slabs parallel to the megascopically visible plane structure. Thin hornblende prisms, some black biotite, variable amounts of chlorite, either as subparallel scales or as metacrysts in random orientation, greenish-gray clinozoisite and epidote, as well as a few metacrysts of garnet and magnetite are seen with the naked eye. Light-colored minerals are usually too small to allow identification in the field. On the south spur of hill 991′, about a quarter of a mile southeast of Shelburne Falls, and directly northeast of the State Police barracks on U. S. highway no. 2, the amphibolite near the crest contains a large mass of a compact, medium-grained rock that resembles metagabbro. A similar rock is exposed on the east slope of West Mountain, a little north of the large bare cliff. Near by there are groups of exceedingly fine-grained layers, in which chlorite has largely replaced hornblende, and metacrysts of chlorite and of glassy plagioclase are scattered through the rock.

Commonly the dark layers are interbedded with white lenses of an aggregate of quartz and feldspar, or the light-colored minerals may form a "pepper and salt" pattern in some layers. Near the northeastern contact, from U. S. highway no. 2 to High Ledge (Shelburne Falls quadrangle), the amphibolite contains chloritic phases, in which the proportions of hornblende and chlorite vary within wide limits. Some layers are almost pure chlorite, in coarse blades and bunches. Others display magnetite metacrysts, up to a quarter of an inch across, amidst irregular clusters of coarse chlorite. Garnet metacrysts reach half an inch in diameter in some layer groups, and in a brush pasture, 600 feet southeast of the summit of Massaemet Mountain, fresh garnets occur in the same ledge with partly or completely replaced garnets. The metacrysts are surrounded by shells of quartz and feldspar and have been altered to fine-grained aggregates of chlorite and quartz. Between these dark layers are others composed largely of quartz and feldspar.

Near the western border of the dome another zone of chloritic rocks displays breccialike structures. They justify the tentative assumption that the amphibolite series is of metavolcanic origin. For instance, the southeasternmost outcrop on the long ridge that ends north of Deerfield River, about half a mile northwest of East

FIGURE 1. INTENSELY FOLDED INJECTION ZONE IN BED OF DEERFIELD RIVER AT SHELBURNE FALLS
Looking northwest. Photograph adjoins lower left-hand corner of Plate 7.

FIGURE 2. NORTHEASTERN PORTION OF GNEISS LEDGE, BED OF DEERFIELD RIVER AT SHELBURNE FALLS
Looking north. Note isoclinal folds of dark amphibolite, shown in detail on Plate 7.

STRUCTURES IN GNEISS

FIGURE 1. LEDGE OF QUARTZ DIORITE GNEISS
Six hundred feet north of U. S. highway no. 2, south slope of hill 1103', Shelburne Falls quadrangle, Massachusetts. Looking south. The smooth surface is a funnel joint of the gneiss dome, dipping at 70° into it. Gneiss layers dip at low angles to the left.

FIGURE 2. LEDGE OF CONWAY SCHIST WITH TWO RESISTANT BEDS OF ZOISITE-GARNET AMPHIBOLITE
(At hammer, and to left of center in middle distance.) East shore of North River at Shattuckville, Colrain quadrangle, Massachusetts. Looking northwest.

FIGURE 3. UPPER CONTACT OF A HORIZONTAL 25-FOOT SILL OF QUARTZ DIORITE GNEISS
On eastern slope of West Mountain, Shelburne Falls quadrangle, Massachusetts. Looking north. Upper third of bluff is intensely folded chloritic amphibolite, flat-lying limbs are floored by sill.

Charlemont (border of Heath and Ashfield quadrangles), consists of normal amphibolite with a lens about 13 feet thick, exposed along the strike for 50 feet, in which scores of light-gray, fine-grained fragments are embedded in a darker, chlorite-biotite-quartz groundmass, with garnets scattered irregularly through it. The fragments

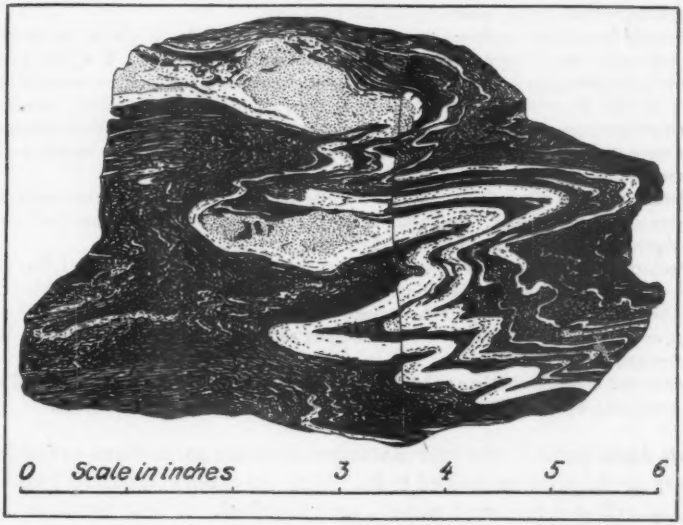

FIGURE 2.—*Polished specimen of folded amphibolite*

Northeastern slope of Goodnow Mountain, Ashfield quadrangle, Massachusetts. Dark: amphibolite; white: layers of quartz dioritic composition; gray (stippling): lenses of clinozoisite.

lack sharp borders, but a few have internal foliation at an angle to the orientation of the surrounding chlorite blades. The fragments vary in size from about a cubic inch to flat slabs, 1–2 inches thick, and 4–6 inches long. Where many fragments lie close together, the chloritic groundmass winds in twisted films between them. At the northern slope of hill 1060′, northeast spur of Walnut Hill (Ashfield quadrangle), very similar rocks are seen, about 30 stratigraphic feet below the dome contact. Some of the fragments are siliceous, others are more chloritic than the groundmass which here contains more quartz and magnetite than at the other locality.

In several exposures, lenticular masses of greenish-gray clinozoisite are conspicuous. They vary in size from thin lenses, a fraction of an inch thick (Fig. 2), to ellipsoidal bodies, 3 feet or more in diameter, and several of them may lie in a row. The absence of any diagnostic rock varieties in their surroundings makes their interpretation difficult, but perhaps these lenses, like the breccia zones, may be altered mafic volcanic rocks. Unquestionably sedimentary rock types, such as mica schist, have nowhere been noted in the amphibolite series.

MICROSCOPIC DESCRIPTION: The normal amphibolite is a granoblastic aggregate of hornblende and subordinate amounts of quartz and plagioclase. Layering is distinct, and the great majority

of the hornblende prisms lie in the foliation plane. Linear orientation within the foliation plane is rarely pronounced. A few flakes of brown biotite are common, and, even in the freshest specimens, a small amount of hornblende has been chloritized. Garnet and magnetite occur as euhedral or subhedral metacrysts, 1–2 mm. across. In some specimens these two minerals increase to 3–4 per cent of the rock. Clinozoisite and epidote vary considerably in amount. In some of the lenticular masses, they are almost the only minerals present. Accessory minerals of the amphibolite are: zircon, apatite, ilmenite, rutile, sphene, pyrite, and carbonate.

Hornblende from eight specimens was separated for determination of optical properties. The pleochroism varies only in degrees from the usual X = light greenish yellow, Y = light green, Z = bluish green; β varies from 1.643 to 1.677, and the birefringence is the common one of about .019. or Z:c = 25°–30°, 2V (−) large, r > v, weak. Even in the freshest amphibolites, a small amount of hornblende has been marginally altered to colorless amphibole in identical optical orientation and with the same extinction angles as the parent grains. Indices of the colorless variety are slightly lower than those of the green hornblende but were not specifically determined.

Plagioclase varies in composition. Bytownite, $ab_{22}\ an_{78}$, was determined in the coarse metagabbroic phase on West Mountain. Sodic labradorite and sodic andesine were found in 3 specimens, but 16 other samples contain oligoclase near the composition, $ab_{85}\ an_{15}$.

Clinozoisite in lenticular masses forms small equant grains, with α: 1.727, β: 1.731, γ: 1.737, optically negative, r < v, weak, indicating about 9 per cent of the iron silicate molecule (Winchell and Winchell, 1927, p. 355). Chlorite shows weak pleochroism, light green to colorless, and the usual deep-blue or smoky-olive interference colors, changing to lavender in pleochroic haloes. No interference figure could be obtained.

Hydrothermal alteration in the amphibolite has produced a dull grayish-green felt of chlorite and sericitic muscovite, with variable amounts of secondary iron oxide, calcite, and quartz.

Quartz-diorite gneiss.—The least contaminated phases are medium- to fine-grained, light-gray or whitish, even-grained rocks. With the naked eye, quartz, feldspar, and biotite, as well as a few small garnets, are recognized. A little hornblende is also present in most specimens. Layering is recognizable in all outcrops, and with increase of mafic minerals the rock becomes a minutely foliated injection gneiss in which the mineral proportions vary within wide limits. Two specimens of siliceous, seemingly uncontaminated quartz diorite were analyzed (Table 1, analyses I and II). Judging from Chapman's description (1942, p. 898, 902) this rock is somewhat similar to the quartz diorite gneiss of the Unity domes in southwestern New Hampshire (Fig. 1).

Although the low amount of potash appears to be common to all siliceous components of the gneiss complex, and justifies the designation, quartz diorite, for them, it is not certain that all the thin, concordant layers of this rock within amphibolite zones are of intrusive origin. Some of them display so much quartz and garnet that they may represent volcanics of more siliceous composition than the amphibolite. With this exception, however, the bulk of the siliceous component of the gneiss complex is believed to be the product of the intrusion by a quartz-dioritic magma and its more volatile derivatives. Intrusive, cross cutting contacts of the quartz diorite are very rare, but an example is illustrated in Figure 3.

Microscopic Description: Equant, or slightly flattened, anhedral grains of quartz and plagioclase constitute the bulk of the siliceous phases. The average grain size is nearly 1 mm., but less in fine-grained layers. These two minerals make up nearly 90 per cent of the rock, and quartz is slightly more abundant than plagioclase. The remainder, about 5–10 per cent, is made up of biotite, in evenly spaced, single grains, well oriented parallel to the megascopic plane structure, and smaller

TABLE 1.—*Chemical analyses of three igneous rocks*

	I	II	III
SiO_2	75.95	78.79	70.04
Al_2O_3	13.59	11.53	16.74
Fe_2O_3	.29	1.46	.08
FeO	1.96	1.16	1.72
MgO	.38	.37	1.44
CaO	1.91	1.94	3.51
Na_2O	4.67	4.47	4.58
K_2O	.55	.10	.92
H_2O-	.60	.41	.57
H_2O+	.03	.05	.04
TiO_2	.16	.14	.28
P_2O_5	.05	.02	.08
MnO	.08	.04	.03
Totals	100.22	100.48	100.03
NORMS			
Quartz	40.68	47.40	29.40
Orthoclase	3.37	.56	5.56
Albite	39.30	37.73	38.78
Anorthite	9.45	9.73	16.40
Corundum	1.84	.51	2.14
Hyp. $FeSiO_3$	3.17	.79	2.51
Hyp. $MgSiO_3$	1.00	.90	3.60
Magnetite	.46	2.09	.23
Ilmenite	.30	.30	.61
Apatite	—	—	.34
H_2O	.60	.46	.57
Totals	100.17	100.47	100.14
Normative plag	$ab_{81}an_{19}$	$ab_{80}an_{20}$	$ab_{70}an_{30}$

I Quartz diorite gneiss, cut in Conway Road, due east of hilltop 1005′, 1½ miles S.-SE. of Shelburne Falls, Shelburne Falls quadrangle.
II Siliceous quartz diorite gneiss, ca. 100 stratigraphic feet below schist contact, NE. slope, Goodnow Mountain, Ashfield quadrangle.
III Quartz diorite porphyry dike, discordant in Conway schist. Bed of Sluice Brook, ca. 500 feet S. of U. S. highway no. 2. Shelburne Falls quadrangle.
(Analyses by Lee C. Peck, Minneapolis)

amounts of hornblende, magnetite, and variable amounts of epidote, chlorite, and garnet. Accessories are zircon, apatite, ilmenite, and sphene.

Potash feldspar is rare, although a small amount of muscovite, in rather large poikiloblasts, may be a product of late recrystallization of potash feldspar. Where found, potash feldspar occurs as small intergranular blebs, mostly microcline, and in one section it is perthitic, with small grains of albiclase.

Indices of refraction of plagioclase, obtained from grains of 25 specimens, give a range of composition from oligoclase, $ab_{74}an_{26}$, to albite, $ab_{98}an_{02}$, with the majority between ab_{82} and ab_{88}, in fair agreement with the normative plagioclase. In a few specimens with subporphyritic texture, the composition of phenocrysts is medium oligoclase in the center, with shells 5 per cent more sodic, or with oscillatory zoning. Many plagioclase grains are untwinned and so fresh that they are difficult

to distinguish from quartz, a fact commented on by Emerson (1898a, p. 39). In the twinned ones, pericline lamellae are more widespread than albite lamellae.

Biotite shows pleochroism smoky olive green to straw, and many grains are slightly chloritized. Hornblende has essentially the same properties as those in the amphibolite. In one single specimen from a "boss" of quartz diorite in the center of the ledge in Deerfield River at Shelburne Falls, a few grains of a deep bluish-green hornblende were noted, with strong dispersion, r > v, and 2V (+)

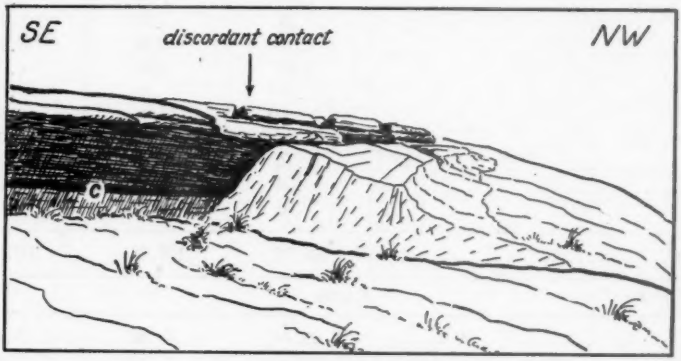

FIGURE 3.—*Ledge of gneiss*

On southern spur of hill 991′, one mile southeast of Shelburne Falls, showing discordant contact of dikelike zone of quartz diorite gneiss. At c, quartz diorite underlies amphibolite (black) concordantly, dipping 10° S. Below arrow, amphibolite layers are cut off by gneiss.

ca. 35°. Hornblende in stubby prismatic grains, like chlorite and biotite, shows good parallel orientation in the direction of the foliation. Some grains of epidote and magnetite are commonly adjacent to it.

Pegmatites and quartz veins.—Pegmatitic dikes, veins, and lenses are fairly numerous in the gneiss complex. They may be straight, folded, concordant, or discordant, and in some ledges they cross each other, although there is no evidence that an appreciable hiatus separates their crystallization. Discordant pegmatites may have gradational, ill-defined contacts, but others are sharp, and the same differences were noted among concordant lenses. Thicknesses range up to 6 feet, and veins 2–4 inches across are most common. In some crosscutting dikes, the minerals display a feeble foliation parallel to the dike walls, but a few have micaceous films parallel to the foliation in the surrounding gneiss, across the contacts. Presumably the dikes were emplaced during the closing stage of the quartz diorite intrusion.

The pegmatites are composed of quartz and oligoclase-albite (ab_{87} – ab_{96}) in roughly equal proportions, and about 10 per cent of potash feldspar. Muscovite varies in amount from 1–10 per cent, and biotite, chlorite, magnetite, tourmaline, epidote, and pyrite are present in variable but usually small amounts. Occasionally, small open vugs in pegmatites are coated with acicular quartz prisms, small oligoclase crystals, and fine scales of muscovite.

Quartz veins, or quartz-feldspar veins with small amounts of feldspar, are also common, and the smallest endings of many pegmatite lenses which are scattered through injection zones seem to be composed mainly of quartz. Several quartz

veins were noted which are folded with the twisted foliation in complex zones of mixing, and others occupy the position of gash veins (Pl. 7). It is concluded that at least some quartz was precipitated during the folding of the gneiss complex, but most of the veins seem to be of approximately the same age as the pegmatites.

CONWAY SCHIST

General Description.—The gneiss dome is surrounded by the Conway schist, a black to dark-gray, medium- to fine-grained argillaceous rock, in which megascopically black biotite, muscovite, brownish-red garnet, chlorite, quartz, and some tourmaline are recognized. Schistosity is well displayed in all outcrops, striking and dipping parallel to the innumerable interbeds of quartzitic, calcareous, and actinolitic composition, which are characteristic in this formation. After examining scores of large, clean surfaces of the schist, the writer is satisfied that in the present area there is no widespread flow cleavage across the original stratification planes. The visible schistosity in pure argillaceous beds appears to be the reproduction of the bedding planes in the form of coarsened and enlarged flakes of mica, which have retained essentially the same orientation as those individuals that grew early during the metamorphism of the rock. In a few polished slabs from the western slope of Mary Lyon Hill (Ashfield quadrangle), and another from the east slope of the ridge in the extreme southwest corner of Colrain quadrangle, there is a feeble development of micaceous films across layers of calcareous schist and along the apices of small folds, accompanied by very minute displacements of layers. If shearing of considerable magnitude has occurred in the rock, it must have taken place along bedding planes for the most part, and not in shear planes across them (Fig. 8).

Almost the only metacrysts in the schist are euhedral or subhedral garnets which are rarely more than a quarter of an inch across. Staurolite and kyanite are extremely rare, and the crystals are only a few millimeters long. Although biotite is present in all outcrops of argillaceous phases, metacrysts of the mineral are small and inconspicuous. A search for isograds of metacrysts was unsuccessful, and there is no systematic increase or decrease in the metamorphic rank of the formation with reference to the dome. Other significant changes in mineral composition, however, will be described.

MICROSCOPIC DESCRIPTION: In 64 thin sections of the schist, the principal minerals, in order of decreasing abundance, are muscovite, reddish-brown biotite, quartz, plagioclase, chlorite, and garnet. Zoisite is rarely absent and becomes an important mineral in some places. Graphitic dust is plentiful in the argillaceous phases of the schist, and tourmaline, apatite, sphene, rutile, magnetite, pyrite, and carbonate are present in minor amounts, and in variable combinations and proportions.

Thin sections seen in plain polarized light exhibit a well-foliated, dusty groundmass of muscovite, with minor amounts of biotite and chlorite. Between them are thin layers and films of quartz, and scattered metacrysts of garnet. The dust in the groundmass of some sections is in straight, parallel tracts, and in curving wisps in others, bending around garnets or little clusters of quartz. Tiny prisms of tourmaline, commonly with color zoning, are present in the micaceous zones of almost every slide. Under crossed nicols, a large amount of plagioclase is at once noticed. In some layers, the mineral amounts to about 50 per cent of the rock. The crystals are replete with graphitic dust, like most of the muscovite, and are very difficult to recognize megascopically, even on fresh surfaces of the schist. The cleavage cracks of the plagioclase are effectively obscured by the dust. The mineral forms thin plates, rarely more than 5 mm. long, within the foliation planes. Chessboard structure, wavy extinction, and the abundance of dust make the determination of the composition

difficult. In 17 thin sections and powdered samples, the composition varied from oligoclase, $ab_{72}an_{28}$, to albite, $ab_{96}an_{04}$; in more calcareous interbeds the composition is andesine, and even labradorite, $ab_{34}an_{66}$.

Biotite, muscovite, and chlorite occur both as thin, dusty, curved scales, parallel to the twisting foliation, and as crosscutting, larger straight blades of later age. Transverse metacrysts of chlorite, in particular, with straight cleavage across the curved rows of graphitic dust, leave no doubt that the small-scale folds of the groundmass were established before the crystallization of these minerals ceased (Pl. 5, fig. 1). Garnet metacrysts commonly contain inclusions of dust, either as squarish, straight dodecahedral layers, or as an outer, spherical shell. Small blebs of quartz are prominent in garnets of some slides, and sigmoidal curves show slight rotation of the growing metacrysts (Pl. 5, fig. 2). Chloritization of the mineral is discussed on a later page.

In agreement with the field observations, staurolite and kyanite are unusual, inconspicuous minerals, rarely exceeding 2 mm. in length, and of almost equant shape. Zoisite and actinolite are seen in at least a few grains in most sections. They become important constituents in the more calcareous interbeds.

Calcareous interbeds and amphibolite.—Emerson (1898a, p. 185–196; 1917, p. 46, 47) described "subordinate beds in the Conway schist" of gneiss, whetstone schist, limestone, and amphibolite. Calcareous layers, from a fraction of an inch to over 30 feet in thickness, are the lithologically most characteristic phases of this formation. Their abundance farther north suggested to Richardson the designation, Waits River "limestone" (1906, p. 86). The rocks have been adequately described by Emerson. Calcareous lenses in the vicinity of the Shelburne Falls dome are not particularly numerous, and, as they do not seem to occur along any stratigraphic horizons, they have not been specially designated on Plate 1. The rocks weather out with characteristically rough surfaces because of the many small quartz grains that are everywhere mixed with the carbonates. Two thin sections show a granoblastic texture, composed of about equal parts of calcite and quartz, heavily charged with graphitic dust. Actinolite, pyrite, zoisite, chlorite, sphene, and muscovite occur in small amounts.

Actinolitic layers, from fractions of an inch to several feet thick, are widespread. The rather coarse-grained rocks weather as resistant benches and miniature cuestas on mountain slopes (Pl. 3, fig. 2). Contrary to expectations, these zones were nowhere seen near calcitic lenses, and the borders of actinolitic layers are usually in sharp contact with argillaceous zones. Actinolitic hornblende in these zones forms stubby prisms in random orientation; they are usually penetrated by gray prisms of zoisite and enclose garnets, 3–4 mm. in diameter. Microscopically, considerable labradorite, $ab_{33}an_{67}$, is seen in irregular grains or more continuous lenticular zones, and, in a ledge on the east shore of North River at Shattuckville (Colrain quadrangle), pink sphene occurs in equant grains, 4–5 mm. across. Thin veins of quartz, labradorite, and zoisite traverse the layers in many places. Apparently, this rock ruptured during a comparatively early stage in the metamorphism of the rocks, and into the gaping fractures minerals were deposited by circulating solutions.

Subordinate phases.—Light gray, fine-grained feldspathic lenses, composed of andesine, $ab_{62}an_{38}$, quartz, garnet, chlorite, zoisite, and minor amounts of biotite and muscovite, were noted in the ridge southeast of Pocumtuck Mountain (Heath quadrangle); elsewhere in the schist, thin quartzitic lenses, and others of quartz-muscovite schist, are of local importance.

At the west-southwest base of hill 1360′, east of Bray Road, and about half a mile due east of Moonshine Hill (Ashfield quadrangle), the schist contains a lens of what is believed to be an igneous rock. A 2-foot layer of a light-gray, fine-grained, slightly porphyritic rock, conformably folded with the schist, is exposed over 25 feet along the strike. Contact effects on the surrounding schist are lacking.

A thin section shows a fine-grained groundmass of quartz and plagioclase grains, about .1 mm. in size, and about 18 per cent of phenocrysts of oligoclase, $ab_{78}an_{22}$, ranging in diameter up to 2 mm. Chessboard structure, partial sericitization, and zoning are common, and the borders are about 3 per cent more sodic than the cores. Potash feldspar could not be determined with certainty in the thin section. About 10 per cent of muscovite and some biotite form thin scales in perfect alignment with a megascopically visible foliation parallel to the borders of the lens. The mineral composition of this rock is strikingly similar to that of the quartz diorite porphyry dikes described below, and the rock may be a concordant dike of this group. However, as it has been folded with the Conway schist, it may represent an earlier, squeezed dike.

Quartz veins.—If the gneiss is intrusive into the schist, it would be reasonable to expect quartz veins near the gneiss contact to contain appreciable amounts of feldspar or other high-temperature minerals. If the gneiss is older than the schist, there need not be any relationship between contact and mineral composition of veins.

Quartz veins penetrate the schist in virtually every larger outcrop. Some are folded conformably with schist layers, others cut across the layers but are slightly deformed themselves, still others are discordant and straight. From thin crack fillings, there are gradations to larger lenticular veins, about 2–3 feet in thickness. Few can be walked out for more than 40 feet. Where quartz veins widen into pods, a small amount of muscovite is commonly seen. In a few instances there are also small garnets, groups of chalk-white feldspar, making irregular clusters 1 cm. or so across, and an occasional grain of tourmaline or kyanite. Oligoclase was determined in four thin sections and a few powdered grains: the composition varies from $ab_{70}an_{30}$ to $ab_{89}an_{11}$. Potash feldspar was not found, although the degree of sericitization of some grains precluded accurate determination. The amount of feldspar in quartz veins is believed not to exceed 10 per cent, and is generally much less. Rough estimates in the field suggest that there are about 150–200 barren quartz veins for every feldspar-bearing one, and this estimate applies to exposures near and far from the gneiss. As a further check, veins were studied as far as 5 miles from the contact, in a southerly, southwesterly, and northerly direction from the dome. No change in the observable frequency of feldspar-bearing veins could be found. For instance, in two traverses of Mary Lyon Hill, $2\frac{1}{4}$ miles southwest of the dome, four feldspar-bearing pods in quartz veins were noted among dozens of barren veins and lenses. In the hills between Conway and the summit known as The Colonel (Shelburne Falls quadrangle, outside Plate 1), $3\frac{1}{2}$–5 miles from the dome, 11 feldspar-bearing veins were seen in an area of about 1 square mile. On the other hand, about $2\frac{1}{2}$ miles north of the dome, in the ridge west of Foundry Village, and about half a mile northwest of Griswoldville (Colrain quadrangle), there begins a group of pegmatites, high in potash feldspar and light-green muscovite, which appear to be of igneous derivation, but no such pegmatites crop out farther south, near the gneiss dome. From the nature and distribution of the quartz veins, it is concluded that they are not genetically related

to the igneous component of the Shelburne Falls gneiss, but are probably related to the processes that converted the Conway formation from an argillaceous-calcareous sediment to the metamorphic schist. This agrees with the absence of any isograds in the schist of this area.

Quartz veins near amphibolitic layers in the schist contain much zoisite. Sheaves and bunches of slender gray prisms, as much as 8 inches long, penetrate the quartz in irregular, pocketlike masses. Many prisms are fractured and bent, but the deformed crystals permit careful removal from the quartz. Emerson (1895, p. 177–180; 1898a, p. 184) called attention to the occurrence of zoisite crystals in the Conway schist. The writer collected good material at the following localities: about 300 feet west of Tower Road, and a tenth of a mile north of U. S. highway no. 2 (Shelburne Falls quadrangle); south slope of southwest spur of hill 1237′, at elevation of about 900 feet and a little west of meridian 72° 42′ 30″ (Colrain quadrangle); summit ledges of Houghton Hill (Colrain quadrangle); also in a long belt of quartz veins on the north-northeast spur of Patten Hill (Colrain quadrangle).

Indices of refraction of a crystal from the second locality mentioned above are: α, 1.697; β, 1.698; γ, 1.703; 2V (+) 10°–40°; r < v, strong. According to Winchell and Winchell (1927, p. 353–354), it is essentially an iron-free zoisite.

DIKE ROCKS

Pertinent data for nine dikes seen in this area are tabulated in Table 2. All but dike no. 7 are in the schist, and all but dike no. 1 are discordant. A chemical analysis of dike no. 2 is given in Table 1, No. III. Although dike no. 2 is faulted on a small scale, the contacts of all dikes are straight, and it must be assumed that the various minor flexures of the schist had ceased before the dikes were emplaced. No dike can be traced beyond the outcrop in which it is exposed, and a systematic areal survey would probably bring to light many more dikes. In hand specimens, the fresh rocks are fine-grained, grayish or slightly purplish; even-grained or slightly porphyritic; and numerous small biotite flakes are oriented parallel to the contact walls.

Microscopic Description: A groundmass of equant quartz and plagioclase grains, about $\frac{1}{10}$ mm. in size, contains abundant phenocrysts of plagioclase, 1–2 mm. across (Pl. 5, fig. 3). Apparently both the plagioclase groundmass and the phenocrysts have the same composition, oligoclase $ab_{70-72}an_{30-28}$, which agrees with the normative plagioclase, $ab_{71}an_{29}$. Oscillatory zoning of phenocrysts is common, but the difference in composition is slight. Traces of magnetite and pyrite and an occasional flake of muscovite and chlorite complete the mineral composition.

Both the dike rocks and the igneous component of the Shelburne Falls gneiss are low in potash, but the meaning of this similarity is not clear. Through the eastern Green Mountains and Berkshire Hills are scattered many kinds of dike rocks and intrusives. Until much more detailed information is available on their areal distribution, the genetic relations of the dikes are quite vague. In most of them biotite constitutes less than 5 per cent. These might be termed quartz diorite porphyry, or soda granite porphyry, although in a few others where biotite increases to over 10 per cent, the term kersantite might be considered. Fifteen miles south-southeast of Shelburne Falls is a larger mass of quartz diorite, Emerson's Belchertown tonalite (1898a, p. 331–

TABLE 2.—*Dike rocks*

No. of dike	Locality	Strike & dip	Thickness	Remarks
1	Sluice Brook, south of U. S. highway no. 2 (Shelburne Falls quadrangle)	N.37°E., dip 32° E.-SE.	3 feet	Concordant, fresh dike. Foliation parallel to contacts.
2	As no. 1, ca. 200 feet farther south	N.-S., to N.23°W., dip 55°W.-SW.	1 foot	Discordant, fresh dike, faulted into four parts. Foliation parallel to contacts. Chemical analysis, Table 1, III.
3	As nos. 1 and 2, near mouth of brook	N.38°W., dip 47° SW.	8 inches	Discordant, crooked dike, foliation parallel to contacts.
4	Railroad cut, ½ mile NW. of Bardwell (Shelburne Falls quadrangle)	N.32°E., vertical	1–3 feet	Discordant, in places concordant; foliation parallel to contacts. Lenses out on N. side of cut, and varies in direction.
5	150 feet NE. of top, hill 1434′, 2 miles S.-SW. of Shelburne Falls (Shelburne Falls quadrangle)	N.7°W., dip 25° W.	4 feet	Discordant, fresh dike; foliation parallel to contacts. No megascopic contact effects.
6	Ca. 2500′ S.-SW. of High Ledge, at approximate elevation of 850 feet (Shelburne Falls quadrangle)	N.60°E., dip 48° N.W.	3 inches	Discordant, sheared dike, of irregular thickness and direction. Foliation parallel to contacts. Micacized, garnetiferous rock.
7	Ca. 1700 feet SW. of High Ledge, at approximate elevation of 750 feet (Shelburne Falls quadrangle	Low N.-NW. dip	6 inches	Discordant dike, foliation parallel to contacts. Lower 2½ inches replaced by black tourmaline and quartz.
8	At gneiss contact, SE. slope of Goodnow Mountain (Ashfield quadrangle)	N.17°W., dip 33°-W.-SW.	2½ feet	Discordant dike, foliation parallel to contacts. Garnetiferous rock, locally tourmalinized.
9	Rise 1350′; 1000′ north of Houghton Hill (Colrain quadrangle)	N.17°W., vertical	8 inches	Discordant dike, foliation parallel to contacts.

339; 1898b, p. 6, and map). Conceivably, these dikes are offshoots of it, even though hornblende seems to be lacking in the dikes, but in cartain portions of the tonalite the mineral is also rare. Moreover, the original composition of at least some of the dikes has been altered; if the rocks contained potash feldspar, it must have been altered to muscovite North of the Shelburne Falls dome, in southeastern Vermont, are other outcrops of intrusives, but very few have as yet been studied in detail (Church, 1937; Maynard, 1934). About 7 miles northeast of the dome, in the northwestern corner of Bernardston quadrangle, Massachusetts, are a number of dikes in the Conway schist. They resemble the ones here described, but are much more altered (Unpublished field work by Balk for the U. S. Geological Survey).

ROCKS AT DOME CONTACT

General statement.—For the determination of the age relations of the gneiss and schist, observations along the contact zone of the gneiss are, of course, of special importance. The excellent exposures allow detailed examinations.

Silicified gneiss.—The till which covers most of the interior of the dome fades out as the encircling escarpment is approached. At its base, large talus blocks of gneiss are passed, and, at the upper reaches of the talus, rocks of the gneiss complex crop out, either in subhorizontal benches or in steep-walled ledges, depending on whether the slope is gentle or steep, and whether or not the gneiss is intensely fractured. Rocks about 200 stratigraphic feet below the schist contact do not differ from normal types of the gneiss as seen in the interior; but, as they are followed higher up, the surfaces of ledges show limonite veneers, and joints are commonly coated with thin films of quartz with, or without, magnetite and chlorite. Specimens of quartz diorite gneiss, obtained from this zone, are slightly lighter than the normal rock, the amount of biotite becomes less, and instead little green or brown spots are seen, which consist of chlorite or limonitized pyrite. Some layers of the rock show conspicuous thin films of quartz, with minute vugs between them.

Amphibolitic layers display similar changes. Layers of chlorite are abundant in some outcrops, whereas, in others, the light-colored minerals increase, and joint faces are deeply limonitized. Near the contact, amphibolite changes into variegated and mottled rocks, in which the original hornblende-bearing layers are reduced to rows of lenses, with fine-grained quartz between. Thin quartz veins, with tourmaline, chlorite, or an occasional garnet, traverse them in many directions, and the last 3 or 4 feet below the contact with the Conway schist consists of an almost structureless mass of pyritized quartz-chlorite-hornblende rock. The changes here described are interpreted as due to silicification and similar alteration of the rocks, and the examination of nine thin sections from this zone seems to confirm this.

MICROSCOPIC DESCRIPTION: Hornblende prisms of amphibolite layers are shattered and replete with quartz blebs; entire hornblende grains, or their margins, have been altered to an actinolitic, light-green variety, and colorless edges of hornblende, as described from the amphibolite are common. Hornblende in certain layers has been completely altered into confused aggregates of chlorite, epidote, and clinozoisite, with iron ore, rutile, and sphene scattered through them. Sericitic muscovite and, locally, carbonate are widespread. In a cut on the west side of Conway Road, about 200 stratigraphic feet below the schist contact, this alteration is well exposed. One portion of an amphibolite layer

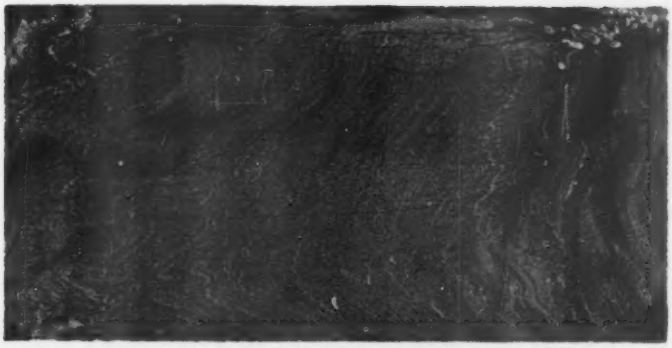

FIGURE 1. LEDGE OF CONWAY SCHIST
In bed of Deerfield River, 200 feet above mouth of North River, Colrain quadrangle, Massachusetts, showing minute crenulations of argillaceous beds. Looking north.

FIGURE 2. CUT IN CONWAY ROAD
Near Buckland-Conway township line, Shelburne Falls quadrangle, Massachusetts. Looking west. Ledge consists of a sill of quartz diorite gneiss, resting on amphibolite dipping gently southwest. Funnel joints dip at high angles to the right. Vertical radiating joints of the dome face the observer.

FIGURE 3. CONFORMABLE CONTACT (AT HANDLE OF HAMMER) OF SILICIFIED AMPHIBOLITIC INJECTION GNEISS AND OVERLYING SILICIFIED CONWAY SCHIST
Northeast slope of Goodnow Mountain, Ashfield quadrangle, Massachusetts. Looking northwest.

CONTORTED SCHIST, JOINTED GNEISS, AND DOME CONTACT

is fresh, the other is altered, and the alteration proceeds along fractures, across the foliation of the fresh amphibolite, or diagonally across layers (Fig. 4). Even under the microscope, the change from the fresh rock to the altered rock is sharp. Small anhedral garnets were seen in altered rock from other outcrops, and there is a possibility that some of these have grown as replacement minerals rather than that they represent remnants of altered original garnets. The original plagioclase has

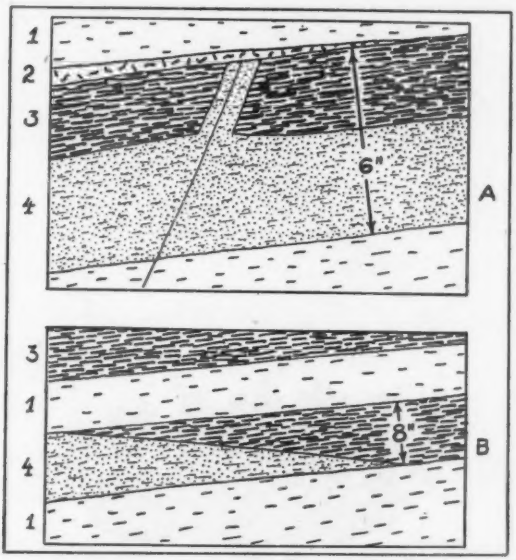

FIGURE 4.—*Secondary alteration of amphibolite*

Near dome border, cut in Conway Road, approximately 170 stratigraphic feet below schist contact, northeastern slope of hill 1176′, Shelburne Falls quadrangle, Massachusetts. 1: quartz diorite gneiss; 2: quartz vein; 3: unaltered amphibolite; 4: altered amphibolite.

A: Lower half of amphibolite, and one-inch zone along a limonite-coated joint, across foliation of amphibolite, are altered to aphanitic, dull greenish-gray aggregate of chlorite, sericite, carbonate, quartz, and pyrite.

B: Altered amphibolite with sharp boundary diagonally across foliation of layer.

also been changed extensively, either through sericitization or by secondary quartz along cleavage cracks and twin lamellae.

Evidence of mechanical deformation other than the small-scale rupturing of the original minerals is rare. However, where the contact is crossed by the Boston and Maine railroad, on the southwest shore of Deerfield River, 2¼ miles southeast of Shelburne Falls, the uppermost half inch of the amphibolite is an aphanitic zone of minute chlorite scales that wrap around angular or rounded fragments of plagioclase, and many blebs of quartz and epidote lie scattered among the chlorite, either singly or in rows parallel to the schistosity (Pl. 5, fig. 4). In the immediately underlying amphibolite, the original minerals have been fractured, feldspar has largely been sericitized or replaced by calcite, clinozoisite, chlorite, and biotite, and all minerals contain blebs of quartz with abundant strain shadows.

The effects of secondary alteration and silicification are more conspicuous in the

amphibolite than in the quartz diorite, but the large amount of secondary quartz is, nevertheless, well displayed in outcrops on Conway Road, a few hundred feet south of the Buckland-Conway township line (Shelburne Falls quadrangle), on the northeast slope of Goodnow Mountain (Ashfield quadrangle), and in the large cliffs north

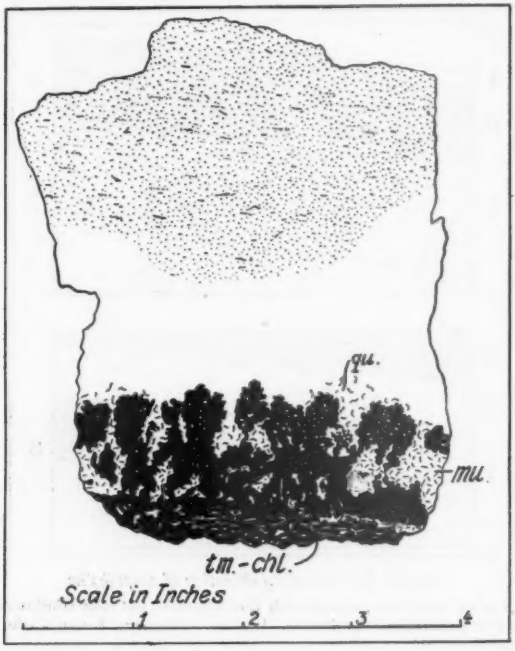

FIGURE 5.—*Polished specimen of tourmalinized dike*

Showing basal portion of tourmalinized quartz diorite porphyry dike, near base of southwest slope of High Ledge, Shelburne Falls quadrangle, Massachusetts. Upper, stippled, portion is normal, fine-grained dike. Middle portion is snow-white aggregate of oligoclase and quartz. At bottom, poikiloblastic crystals of tourmaline, peppered with remnants of oligoclase, and surrounded by irregular pockets of quartz (qu., curving dashes) and muscovite (mu., straight dashes). At lower contact a zone of foliated chlorite and tourmaline (tm.-chl.).

and south of Massaemet Mountain. The high percentage of silica in analysis II (Table 1) is probably due also to quartz infiltration near the contact. This, as well as other specimens, exhibit secondary quartz in microscopic veinlets and grains, flooding the plagioclase.

Quartz diorite porphyry dikes no. 6, 7, and 8 (Table 2), which crop out at or very near the gneiss contact, exhibit interesting forms of replacement. Dike no. 7 (fig. 5) has a bottom zone, half an inch to an inch wide, of black tourmaline, the crystals of which protrude upward into a snow-white zone of plagioclase and quartz, 2 inches wide, from which every trace of dark minerals has disappeared (Pl. 6, fig. 1). The upper border of the white zone is slightly wavy, and gradational within about 2 mm. into the normal, gray, biotite-bearing porphyry dike. Walls of fractures, and a sharp

fault which crosses the dike with a 2-inch displacement, have also been tourmalinized and bleached, and chlorite has been precipitated along the bottom contact of the dike. The schist and amphibolite at the contact of dike no. 8 have been silicified, and pockets of black tourmaline and single garnets have developed inside the dike. Dike no. 6 has been so muscovitized in places that hand specimens might at first be mistaken for a quartz-muscovite schist.

FIGURE 6.—*Contact of gneiss and schist*

Near crest of Goodnow Mountain, Ashfield quadrangle, Massachusetts. Conway schist (overhanging ledge on right-hand side) dips 40° southwest, perhaps unconformably with underlying crumpled layers of injection gneiss. Two-foot interval at contact is concealed.

These observations, to which more could have been added, suggest to the writer that near the contact zone the gneiss has been affected by intense local alteration of primary minerals into a number of characteristic secondary mineral associations which are generally regarded as indicative of hydrothermal processes. Not a single apophysis of the quartz diorite was found in the schist, even though the contact exposures are fresh and continuous so that even small dikes and apophyses would surely have been found. The only igneous rocks encountered at the contact are a few pegmatite veins, composed of quartz, partly sericitized feldspar, and muscovite, with an occasional small garnet. One of the largest veins is exposed at the contact, about 300 feet south of quartz diorite porphyry dike no. 6 (fig. 9). This vein is 4–6 inches thick and can be followed for about 100 feet. Another pegmatite dike accompanies the contact in the same cliff, about 600 feet farther south. A third was noted at the contact at the southwest base of Pocumtuck Mountain (Heath quadrangle). The conclusion seems justified that the changes described are due to the activity of circulating solutions after the intrusion of the quartz diorite and not to the intrusion of the quartz diorite itself.

Although inconclusive in itself, evidence in three additional exposures suggests the former existence of an unconformity between the gneiss and the schist. About 100 feet south of the point where the dome contact passes over the crest of Goodnow Mountain (Ashfield quadrangle), the bottom layer of the schist dips at about 40° S. W., whereas the adjacent injection gneiss (Fig. 6) consists of a succession of small

folds, with axial pitch to the south at about 12°. Accordingly, the limbs vary from westerly to easterly dip at short intervals. A thicker and presumably mechanically stronger quartz diorite layer lies nearly horizontal. Unfortunately, the last 2 feet between the two rocks is concealed, so that possibly the layers of the gneiss bend down where they join the mica schist, but the alternative is an unconformity.

A similar locality is in the bed of Deerfield River, 900 feet north of the power plant, a mile northwest of Shelburne Falls (extreme NW. corner of Shelburne Falls quadrangle). Here the basal schist dips at about 20° N , whereas the injection gneiss below displays a multitude of confused small contortions, so that layers of different stratigraphic position approach the schist. However, the river scour has removed a few inches or feet directly at the contact, and a skeptic might dismiss the evidence as inconclusive.

The third exposure is in the steep contact ledges, about halfway between the summit of Massaemet Mountain and High Ledge (Shelburne Falls quadrangle). Here the injection gneiss, with garnetiferous amphibolite layers, is thrown into several folds of considerable size, the limbs of which, in one place, dip about 70° E., whereas the schist, 3 feet away, dips about 35°. Where the rocks join, the silicification obscures the dip of the foliation, but the limbs of only a few minor crenulations appear to dip parallel to the schist.

Although these three outcrops do not offer compelling evidence for the former existence of an unconformity between gneiss and schist, it should be borne in mind that unconformities are known to have been blotted out by subsequent deformation of the rocks concerned (Balk, 1936, p. 732–736). Such a possibility cannot be ruled out entirely in the present case.

Silicified Schist.—Hand specimens of Conway schist, collected more than about 30 stratigraphic feet above the gneiss contact, do not differ significantly from schist farther away. There is no toughening of the rock as though it had been changed to a hornfels, and there are no metacrysts other than the ubiquitous garnets. The grain size and fabric appear to be normal. However, specimens within 30 feet above the contact contain almost everywhere more quartz; and, within 10 feet above the gneiss, quartz increases so much that the rock resembles a quartz schist. It is therefore difficult in some places to draw the contact with accuracy for both quartz and muscovite have obscured the original mineral composition, producing a superficial similarity between silicified amphibolite and schist.

The study of many specimens and 27 thin sections agrees with observations in the field, but, as might be expected, small-scale effects due to silicification and related mineral alterations are observable farther from the gneiss contact.

MICROSCOPIC DESCRIPTION: The increase in the amount of quartz as the gneiss is approached is shown in several series of sections. The ordinary films and thin lenses of quartz in the Conway schist contain admixtures of graphitic dust, and the rather small grains show optical inhomogeneities and strain shadows. About 200 stratigraphic feet above the gneiss contact—a figure obtained in a section at Pocumtuck Mountain—there appear lenses, about half a mm. thick, of larger, clear, unstrained quartz grains, parallel to the schistosity of the rock. Where they first appear, the area occupied by these clear quartz grains is roughly a tenth of the area of the thin section. In slides about 150 stratigraphic feet above the contact, the proportion increases, although unevenly in layers of different composition. Forty feet above the gneiss, clear quartz occupies about a quarter of the thin section

surface, and at 30 feet, some slides contain as much as half or two-thirds of the area in unstrained dust-free quartz films (Pl. 6, fig. 2). Within the last 30 feet, no further increase was noted, but the schist in this zone does not appear typical because of the large amount of megascopically visible quartz lenticles.

Progressive chloritization of garnets accompanies the silicification of the rock. Although garnets throughout the region show occasional marginal chloritization, this increases noticeably some 150 stratigraphic feet above the gneiss contact, and biotite and chlorite replace the metacrysts. In ledges about 70 stratigraphic feet above the contact, on the southwest slope of Pocumtuck Mountain, about half of nearly every other garnet in the thin section is chloritized, and all have chlorite shells of about a quarter the thickness of the garnet (Pl. 6, figs. 3, 4). In several thin sections, 20–50 feet above the gneiss, the former position and size of garnets are indicated by clusters of quartz blebs and chlorite blades, with a few minute remnants of original garnet still recognizable. Similarly, the original smoky brown-red biotite has been increasingly chloritized as the contact is approached. Secondary chlorite pierces the biotite blades, with or without development of secondary, coarse muscovite.

The changes in the plagioclase of the schist are less noticeable. Although the proportion of the dusty groundmass with plagioclase and muscovite decreases in favor of the lenticles of coarse secondary quartz, the plagioclase grains themselves have not been affected much, save for occasional narrow, clear rims, with slightly lower indices of refraction. Because of the internal dust, the Becke line is often obscured, but very few plagioclase grains seem to have formed comparable to albitization. In some thin sections, the original feldspar grains are penetrated by quartz veinlets, blades of straight muscovite, clusters of sericitic muscovite, tufts of chlorite, and, more rarely, by carbonates.

The changes here described are thought to be characteristic of the Conway formation as a whole. Inasmuch as the lithology of the formation is highly variable, the changes vary in intensity. For example, quartzitic layers have resisted secondary alteration more than purely argillaceous layers, so that garnets in them have occasionally escaped chloritization. To judge from a few thin sections of actinolitic lenses near the contact, these rocks have not been modified as much as amphibolite layers in the gneiss, and the flooding of actinolite with quartz is perhaps the most spectacular feature. No calcitic lenses were found near the contact, and what changes these rocks may have undergone are unknown.

It is thus concluded that the gneiss complex and the Conway schist near the dome border have been permeated by hydrothermal agencies. As the metacrysts of the schist have been altered, silicification must have been later than the main metamorphism of the Conway formation, but there is no necessity for assuming an appreciable time lag between the two stages. The relatively intensive silicification and chloritization near the gneiss border suggest that this surface has been a particularly pervious zone in the earth's crust. A major break (unconformity?) between the two formations might have served as such a zone of mechanical inhomogeneity, and the fracture systems in this zone probably enhanced the permeability.

STRUCTURE WITHIN THE DOME

FOLIATION AND FOLDS

A foliated structure in siliceous quartz diorite gneiss is due to thin films of biotite with, or without, minor amounts of hornblende, magnetite, or epidote. Even where individual grains do not touch each other, a plane structure is brought about by preferential alignment of many scales along common planes. Clean, fresh surfaces of gneiss may display parallelism of minerals that might be overlooked on weathered

faces. In more micaceous phases of the gneiss, individual dark films are continuous over longer distances and follow each other at shorter intervals. Films, seemingly only a grain thick, can be traced in clean surfaces for over 20 or 30 feet as, for instance, in several cuts near the intersection of U. S. highway no. 2 with road no. 112, northwest of Shelburne Falls.

Despite locally intense folding in the gneiss complex, no outcrop was seen in which two plane systems transect each other. Since amphibolite layers and lenses of clinozoisite lie conformably within foliated gneiss, it is believed that the plane structure has developed through recrystallization of original planes of bedding, with or without a certain amount of gliding along these planes. In the rare instances where foliated quartz diorite gneiss cuts across foliation of amphibolite (Fig. 3), the alignment of micas in the igneous rock was probably caused by flowage of a mush-like mixture of solid crystals and intergranular liquid past retarding walls, and the platy minerals obtained stable positions when their largest dimensions lay approximately parallel to the confining walls.

Because of the widespread till cover in the interior of the dome, the strike and dip of the foliation in the interior of the dome cannot be measured everywhere, though the concealed area averages only about half a mile in width. In view of the relatively simple dome structure in the northwestern portion of the dome, a general flattening of the layers and lenses of quartz diorite gneiss near the axis seems a plausible assumption. The structure of the large ledge in Deerfield River at Shelburne Falls is perhaps not typical of the general structure in the gneiss complex. Here a boss of quartz diorite, about 70 feet long and 40 feet wide, and with a NW.-SE. elongation, slopes southwestward at low angles but has a steep northeasterly front. On all sides the amphibolite surrounds the mass concordantly, and, whereas the transition is rather sharp on the northwest, west, and southwest side, there is, on the northeast side, a wide injection zone with exceedingly complex zigzag folds, flexures, and ill-defined contacts between amphibolite and quartz diorite gneiss. Narrow zones of amphibolite, with steep dips, are also seen in a few places on Goodnow Mountain and West Mountain. Sharply compressed folds reconcile between these and the flat-lying sheets and lenses of quartz diorite in the sense that one group of limbs dips steeply, the other gently. It may be assumed that the amphibolite has been pushed up at several places by blunt lenses and projections of the intrusive rock. The thinly bedded, and thus more flexible, amphibolite "groundmass" between them appears to have been forced out in random directions. In these intensely deformed zones the more fluid and mobile fractions of the magma may have produced injection zones. Nevertheless, near the contact, the variable strikes and dips conform closely to the simple structure of the dome (Pl. 4, fig. 3)—with the exceptions noted above.

Zigzag folds and small nearly isoclinal folds are particularly striking features, especially in amphibolitic rocks. Good exposures are in the large ledge at Shelburne Falls, on the east slope of West Mountain (especially in the northern half, rather high up), also on the southeast slope of Goodnow Mountain, and northwest of Massaemet Mountain. For considerable distances, the eye sees nothing but small zigzags and contortions, almost bewildering in their complexity and variability. Strike and dip of limbs, and even the trend and pitch of the axes of these minute folds, vary consid-

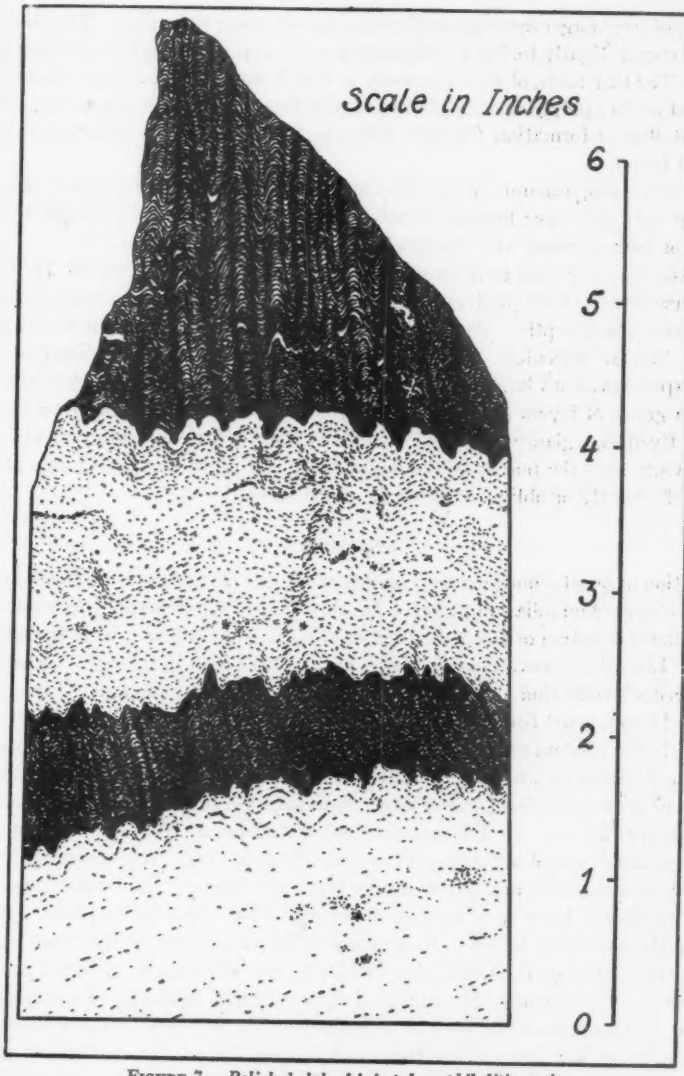

FIGURE 7.—*Polished slab of injected amphibolitic gneiss*

Near crest of Goodnow Mountain, Ashfield quadrangle, Massachusetts. Amphibolite is folded on a minute scale, but the limbs of the folds have not been sheared through; *see* Plate 6, figure 5. Folds in siliceous layers are fewer and less sharp.

erably from one ledge to another, even within distances of a few feet. Hardly anywhere are the limbs sheared off by slip zones, as is so common where phyllitic rocks display such small-scale folds (Fig. 7). Individual thin layers can generally be

walked out over larger outcrops until they lens out along the strike. The absence of shear planes in tightly folded amphibolite zones is confirmed by thin sections (Pl. 6, fig. 5). The tiny folds, of which as many as 4 or 5 can be seen in single thin sections, consist of perfect polygonal arcs of straight, unaltered hornblende prisms, attesting to pre-crystalline deformation (Sander, 1930, p. 263–266). Even microscopic shears were not found.

With increasing amounts of quartz-dioritic material in injection zones, the small folds die out, and wave lengths increase, in agreement with the principle that the lengths of folds increase with the thickness and strength of layers.

The axes of many folds were measured, and a number were plotted (Pl. 1). Accurate measurement of the pitch angle is difficult in many places for exposures near the contact often lack depth. The general direction is sometimes all that can be determined. Similar difficulties arise with the measurement of strike directions, and where exposures afford large, clean surfaces it is better to measure the general extension of a group of layers rather than the innumerable local variations on individual limbs. Even so, a glance at Plate 7 shows that there is little uniformity in the directions. Only near the border of the dome, there is a slight increase of axes of folds that pitch directly or obliquely down the dome surface.

LINEATION

Lineation of quartz diorite gneiss consists of a linear elongation of micaceous aggregates as observed on foliation planes. In amphibolite, the structure is caused by the subparallel orientation of a certain number of hornblende prisms within the foliation planes. Lineation across foliation planes has not been seen in this area. Specimens in the writer's collection show clusters of biotite, 2–5 mm. long and 1–2 mm. wide, about 5–12 mm. apart from each other, in which the linear structure is at once recognized. If the clusters are farther apart, or the ratio of length and width is small, lineation is harder to see, and in many specimens the structure is either lacking or could have been determined only if large, clean foliation surfaces had been exposed in the respective ledges. In different portions of individual outcrops, even of single specimens, the degree of perfection of the structure may vary. A specimen from West Mountain shows biotite in a quartz diorite layer well lineated, but hornblende prisms in an amphibolitic layer lie in random directions within the foliation plane. In general, lineation is easier to see in moderately micaceous phases of the gneiss than in siliceous ones, though the proportion of biotite and other mafic minerals is also of importance. Occasionally, thin streaks of muscovite may be elongated where clusters of biotite and hornblende are equant. As silicification and chloritization of the rocks near the contact have complicated the crystallization of the rocks, the data plotted on Plate 1 are not particularly significant, and it is not advisable to draw too many conclusions from the directions shown.

In many outcrops, there is the common parallelism of axes of folds and lineation, but, owing to the rapid variations in azimuths of both elements, it is impossible to correlate the two structures unless both are visible on the same surface.

Near the contact, lineation has apparently the same tendency of sloping down the dome surface as was noted for axes of folds. Although it would be tempting to specu-

late on the meaning of this orientation, the writer feels that the data are not sufficiently uniform to give a clear picture of the structural plan for the whole mass.

STRUCTURE IN THE CONWAY SCHIST

FOLIATION AND FOLDS

The dome is surrounded by a quaquaversal structure of the Conway schist (Pl. 1). As was stated above, no discrepancy was observed in the orientation of foliation and original bedding. When examined in detail, the argillaceous layers, especially near the gneiss contact, reveal innumerable crinkles and small-scale contortions with wave lengths of fractions of an inch (Pl. 4, fig. 1). Rarely do they reach isoclinal forms, and the fact that more resistant quartzitic and actinolitic interbedded layers lack these crenulations (Fig. 8) suggests that the small-scale deformation of the schist layers is the result of minor adjustments of mechanically weak strata to the general deformation of the more resistant layers near the dome. Instructive exposures showing these small contortions are in the bed of Deerfield River just above the mouth of North River; in wooded cliffs northwest of them (extreme southwest corner of Colrain quadrangle): near the mouth of Sluice Brook, south of U. S. highway no. 2 (Shelburne Falls quadrangle); in a railroad cut on the southwest side of Deerfield River where it cuts the gneiss-schist contact southeast of Shelburne Falls; and in several other outcrops near the contact.

Larger folds near the contact are very rare. Where any were seen, they occur in one rock only, without affecting the structure of the other. (See figures 6 and 9.) The different development of folds on opposite sides of the contact is thought to be corroborative evidence that the deformation of the two rocks took place at different periods.

The structure of the Conway schist farther from the dome poses the interesting question of how the dome structure fits into the general easterly dip of the Conway formation. The present study did not include enough territory to permit a complete answer to it, but a few points are reasonably clear: (1) In the schist northwest of the dome, there is very probably a syncline with a north-south strike. Easterly dip prevails near Charlemont (Hawley quadrangle, Massachusetts, a short distance west of Plate 1), and westerly dip is seen almost 2 miles from the northwestern dome border. Fault zones may be associated with this syncline. (2) Along the northeastern border, the strike of the schist reveals a broad and open, north-northwest pitching syncline in the Catamount Hills (Colrain-Heath quadrangles). Below the eastern limb of this syncline there may be a blunt northward extension of the gneiss dome, inferred from the east-west strike of the northeastern contact near the mouth of North River. (3) On the south and southwest, there is a belt, at least 3½ miles wide, of southward- and southwestward-dipping schist (zone Catlin Lot, "The Colonel", Mount Owen, in Shelburne Falls quadrangle, Mary Lyon Hill, Ashfield quadrangle). Presumably there is also a synclinal zone some distance west or southwest of it. (4) On the southeast and east, the general easterly dip of the schist conforms of course with the regional dip, and there is no special structural problem here. Possibly the doming of the gneiss block has given rise to some normal faults in the schist near the dome bor-

der, but the lack of marker beds and the lack of continuous exposures, even though they are numerous and evenly distributed, does not permit a definite answer to this question.

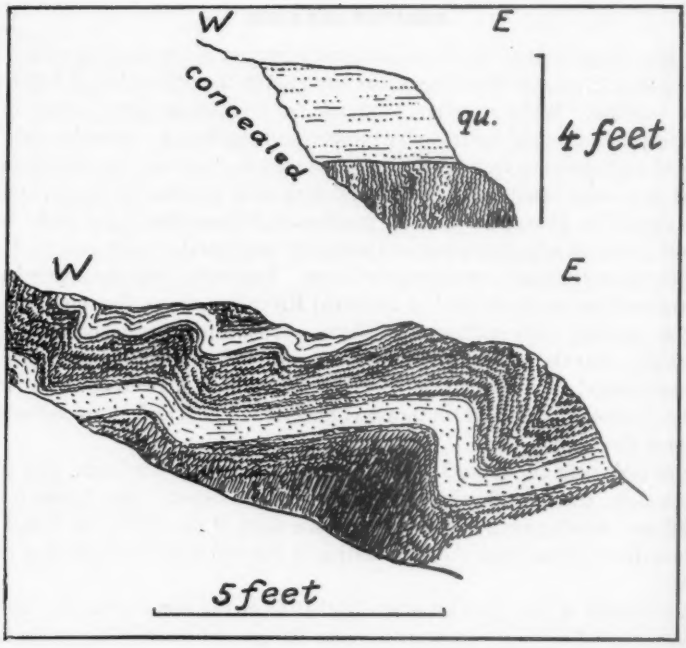

FIGURE 8.—*Crumpled Conway schist*

With quartzitic interbeds, west of power transmission line, extreme southwestern corner of Colrain quadrangle, Massachusetts. Lower picture shows open folds of quartzitic beds, combined with minute wrinkles in argillaceous beds between them. Upper picture, exposed 15 feet east of lower one, shows pseudounconformity between quartzite bed (qu.) and argillaceous layers, caused by slight shearing along base of quartzite bed. In lower picture, this condition has almost been reached at base of quartzite anticline.

LINEATION

Lineation is rarely seen in the Conway schist. Where observed, it is due to minute wrinkles of the muscovite foliae in subparallel directions, or may be recognized by a common orientation of the longer dimensions of individual biotite flakes set in the lighter-colored muscovite groundmass. In some instances, several garnet metacrysts may lie in a row parallel to lineation of micas, and limonitized pyrites, or small quartz lenses can also contribute to the visibility of lineation. Where metacrysts and quartz veins occupy a large proportion of the schist, the structure becomes very elusive.

In the Houghton Hills, lineation pitches gently to the northwest, more or less parallel to the pitch of the axis of the syncline. West of the northwestern end of the dome, lineation it pitches southwest in a few outcrops; southwest of the dome, the pitch is to

the southeast; but on the eastern and northeastern flank of the dome there is hardly any lineation in the schist, although the gneiss below displays rather uniform easterly pitch of its linear structure. Thus there is yet another feature of structural independence between the two rocks.

It could be assumed that the lineation is older than the uplift of the dome. If the present directions of the structure are rotated back into their predoming orientations, the lines would strike in a general NW.-SE. direction, but with many local deviations and gaps. Whether or not this orientation is of regional significance is unknown because of our lack of any detailed structural work in this part of the Berkshire Hills. If the lineation developed as a result of the doming, it would indicate moderate lengthening of the schist either directly up the dome or in other directions that may, or may not, have been the direct result of the doming. This uncertainty is also due to lack of structural information on surrounding areas. It is recognized that the silicification of the rocks near the dome border has probably obliterated much of the lineation, and possibly the schist near the gneiss contact has been deformed by stretching along the stratification planes (not by folding) more intensely than its present texture and silicified condition disclose.

FRACTURE SYSTEMS

CROSS JOINTS

In outcrops that show linear structures, cross joints are common, especially in the Conway schist. By definition, the fractures are normal to the linear structure element, and where lineation is parallel to axes of folds, the cross joints are perpendicular to both linear structures. Thus in the hills west of Griswoldville (Pl. 1), where lineation pitches N.-NW., the cross joints strike E.-W. to W.-SW.—E.-NE and dip steeply southward. Conversely, in the vicinity of Mary Lyon Hill, the pitch is southward and southeastward, and accordingly the cross joints dip northward and northeastward. As is common, they cause slight asymmetries in the profiles of individual ledges and even of ridges and hills in that the steep dips of closely spaced fractures lead to relatively steep hill slopes, even to bluffs parallel to individual joints.

In the gneiss complex, cross joints are occasionally observed, but as the directions of the linear structure elements vary over short distances, the joints are poorly developed and short, and without effect on the sculpturing of cliffs.

FRACTURES AT DOME BORDER

Types of fractures.—Outcrops of schist and gneiss, near the dome border, are dissected by many prominent fractures. Two types are recognized: (1) Fractures that strike approximately parallel to the contact, and dip into the dome. They may be termed funnel joints because an ideal, complete fracture is believed to resemble the surface of a funnel. (2) Fractures of perpendicular or steep dip, striking approximately at right angles to the contact. They may be termed radiating joints because they radiate outward from the border of the dome. Systematic relationships between the orientation of these fractures and the dome border, as well as the restriction of the fractures to the border zone, leave little doubt that they are genetically related to the doming of the gneiss complex.

FIGURE 9.—*Contact of silicified gneiss and folded schist*

About 2,000 feet S.-SW. of High Ledge, Shelburne Falls quadrangle, Massachusetts. Pegmatite vein (pe) along contact separates folded schist from unfolded amphibolitic gneiss. Funnel joints dip downward to the right; shaded vertical surfaces are radiating joints of the dome.

Doming of a portion of the earth's crust in the zone of fracturing necessitates funnel joints and radiating joints. Along the former, a dome expands upward; by means of radiating joints, it expands horizontally. That this has been the mechanical function of these joints is shown by the fact that gaping fractures are found among them; and veneers of quartz, chlorite, magnetite, sericite, and stilbite on a number of them

attest to the overlap in time between fracturing and permeation of the rocks by hydrothermal solutions.

Funnel joints.—Fractures of this group are excellently exposed in the continuous steep contact ledges that extend from U. S. highway no. 2 northward to Massaemet Mountain and beyond it towards the mouth of North River. Other good exposures are in the high scarp that culminates in Pocumtuck Mountain (Heath quadrangle), on the northeast slope of Goodnow Mountain, and in many other contact sections of the dome. Figure 9; Plate 4, figure 2; and Plate 3, figure 1 illustrate a few of them. The funnel joints dip at about 65° to 80° into the dome. Thus they strike about parallel to the outward-dipping gneiss contact, but are roughly perpendicular to that plane. Although the main reason for the escarpment around the gneiss dome is probably the silicified condition of the rocks, and the greater resistance of the schist to weathering, nevertheless the steepness of individual contact ledges is due to disintegration of the rocks along these large, smooth fractures. Where they include gaping joints, as on Goodnow Mountain, and south of High Ledge (Shelburne Falls quadrangle), ground water circulates on them, and springs issue at many points from them. Several funnel joints on Goodnow Mountain are coated with dark chlorite-quartz veneers, and minute displacements were noted on a few. Striated joint surfaces on the eastern cliff of West Mountain may belong to the same group, though the distance from the contact makes the origin of these fractures more doubtful. No dikes of quartz diorite, quartz diorite porphyry, or pegmatite were found on funnel joints.

Radiating joints.—Radiating joints are less conspicuous than the funnel joints. However, they dissect the long scarp surfaces into scores of parallel columnar blocks (aided by the dissection through funnel joints). Along many gaping joints of this set, cliffs have disintegrated, and ground-water seepages have joined with surface run off in developing small intermittent rills of water across the rocky slopes of the escarpment. In others that are wide, dry, and deep, snakes, rodents, and foxes have established their dens, secure from enemies and the cold.

A few radiating joints, about 1000 feet north-northwest of the summit of Massaemet Mountain, show subhorizontal striations, but the displacements must be insignificant. Offsets of the contact of the gneiss by radiating joints have not been seen. Thin veneers of quartz, magnetite, and chlorite were seen about 300 feet north of the point where the gneiss contact swings across the crest of Goodnow Mountain.

In the same cliffs these fractures are on an average about 3 to 5 feet apart in certain zones. In some sections they are closely spaced, leading to narrow defiles and ravines in the escarpment, whereas in still other cliffs they are 25 feet and more apart. The figures are difficult to obtain as most of the joints are of limited height. At a level where one joint reaches its highest point, another starts several feet away, extending to higher elevations. The spacing of funnel joints cannot be determined as the ledges lack depth. One or two, rarely more than a dozen fractures, can be seen in individual surfaces (Fig. 9).

It is of course not necessary that radiating or funnel joints strike and dip exactly at right angles to the contact surface. As long as the directions do not deviate appreciably from the ideal ones, fractures can still be considered to belong to one set or the

other. On Plate 1, deviations are seen, although a great majority of the fractures lie close to the theoretically expectable directions. Deviations in the strike of funnel joints are understandable when it is remembered that the contact curves rather sharply in some sections as, for example, south of Massaemet Mountain, west of the mouth of North River, and at the northwest corner of the dome. The intersection of the contact with the earth's surface is not everywhere at the same level, and the symbol for each fracture is of course much longer than the actually observed joint.

Similarly, not all radiating joints form right angles with the contact as it is drawn on Plate 1, and, in this case, another cause for discrepancies should be noted. In at least two sections north and south of the dome, there are fairly uniformly developed cross joints in the Conway schist. Their orientation is such that they may have served as "substitutes" for funnel joints and radiating joints. For example, where the northeastern dome contact makes the sharp bend, three-quarters of a mile southwest of the mouth of North River, the southward-dipping cross joints in the Conway schist have a strike so similar to that of radiating joints at that point that the latter have been largely suppressed in favor of southward-dipping fractures. A short distance southeast, where the contact bends into the east-west strike, the cross joints have the same orientation as funnel joints of the dome. As such they are numerous here, whereas no radiating joints appear in the contact zone.

At the northwest end of the dome, the disposition of the fractures shows another possible relationship. Here the cross joints in the Conway schist dip about 60°–80° NE. Nearby in the gneiss dome, joints of the same northeasterly dip have the strike of radiating joints, although as such they should dip more nearly vertically. No relationship to lineation in the gneiss could be ascertained, and, although exposures in this particular section of the gneiss border are poor, the possibility might be considered of whether cross joints in the schist might have grown, so to speak, into the gneiss. The till cover is, unfortunately, so extensive here that joints in the schist cannot be walked out across the contact into the gneiss. For this reason, the observations are not sufficiently reliable for a more detailed discussion. If two rock formations superimposed on one another could be considered to represent a mechanically homogeneous entity, one might venture to think of a mechanism of fracture propagation, analogous in its final result, though no doubt very different in mechanics, to what has been experimentally obtained by Griggs (1936, p. 552–553) with Solenhofen limestone. However, such a comparison is very inadequate as long as the amount of overburden at the time of doming is unknown.

South of Massaemet Mountain, another combination of joints is noted. Here the cross joints of the gneiss coincide with the position of funnel joints. They are prominently developed but appear to be absent in the overlying Conway schist. Radial fractures, however, traverse both the gneiss and the schist in nearly identical orientations, and without recognizable relationship to structures in either formation.

Joints of uncertain origin.—Fractures with no known angular relationship to the contact, foliation, lineation, or fold elements are difficult or impossible to classify. On Plate 1, only a few of these have been plotted. Emerson (1895, p. 32) mentions north-south striking joints in an old quarry on U. S. highway no. 2, near its junction with highway no. 112, that are coated with babingtonite. In a recent search, the

mineral could not be identified, but highly ferriferous epidote, chlorite, quartz, and stilbite veneer many of these fractures. In the long scarp on the east side of West Mountain, many joints of various strikes and dips are exposed without clear structural relationships to foliation, folds, and lineation of the gneiss.

FAULTS

In the present area, where Quaternary cover obscures much of the bedrock surface, faults appear in individual outcrops only, and, as marker beds in the Conway schist are lacking, it is impossible to trace a fault from one outcrop to another. Neither are there topographic features that require fault zones for explanation. For these reasons, no faults have been inserted on Plate 1, as the plotting even of inferred faults, without sufficient evidence, is often of questionable value. A few individual outcrops of faults may be listed.

Quartz diorite porphyry dike no. 2 is crossed by four faults, with displacements ranging from 21 to 48 inches. The fractures are smooth and tight and lack marginal brecciation. In a railroad cut, 2000 feet northwest of Bardwell (Shelburne Falls quadrangle, outside of Pl. 1), the Conway schist is traversed by a crushed zone, striking N. 10° W., dipping 47° W.-SW., and by another one of N.-S. strike and vertical dip. Relative movements, and magnitude of displacement, cannot be ascertained. Other crushed zones are exposed in other railroad cuts farther northwest. A slip zone, coated with chlorite and quartz, dipping 60° E.-SE., is well exposed in the large, bare ledge high up on the eastern side of West Mountain. Two other fault planes are seen nearby. Striations are approximately down the dip of the planes, and one normal fault shows displacement of 8 inches. Contrary to expectations, the steep eastern face of this mountain does not appear to be caused by a fault for, at the northeastern base, ledges of fresh quartz diorite gneiss extend from the mountain practically uninterruptedly into the lowland to the east. Presumably, the ledge has been caused by ice scour aided perhaps by a zone of closely spaced joints. Minor fractures with striations or small displacements were seen in many other places, but it seems unnecessary to list them.

SUMMARY

The geologic history of the region is thought to consist of the following stages, listed in order from the earliest to the latest:

(1) Volcanic eruptions, in pre-Cambrian, or early Paleozoic time, produced basaltic flows, thin-bedded tuffs, and perhaps pyroclastics.

(2) Intrusion and *lit-par-lit* injection of these rocks by numerous sills and irregular lens-shaped masses of a quartz dioritic magma and its more volatile derivatives converted the volcanic rocks into amphibolites and complex mixed gneisses. At the end of this stage, the sills and foliated mixed zones lay probably flat, but between them there were intensely crumpled and folded zones of amphibolite. This stage of deformation and injection is believed to have ended with the precipitation of pegmatitic dikes and quartz veins.

(3) A period of erosion was followed by submergence and marine deposition in

Conway (Ordovician?) time. Deposition of predominantly argillaceous sedimentary material may have continued through Silurian and possibly even Devonian time, if it is assumed that stratigraphically higher formations originally overlay the Conway formation of this area. Likewise, sedimentation probably started before Conway time in surrounding regions, but these older rocks do not enter the vicinity of the gneiss area.

(4) A regional disturbance of the area east of the axis of the Berkshire Hills had the following results: (a) The argillaceous sedimentary rocks were tilted downward to the east, contorted on a small scale, but apparently not isoclinally folded; (b) All rocks were permeated by hydrothermal solutions which precipitated the metacrysts and other metamorphic minerals in the Conway schist, and converted calcareous lenses into impure marbles and more aluminous marls into actinolitic zoisite-bearing rocks; (c) The rocks were intruded by dikes of the approximate composition of quartz diorite porphyries, or kersantites. This stage probably followed stage 4b closely, because some of the dikes have been silicified, tourmalinized, and micacized; (d) Probably near the end of stage 4b, the gneiss below the Conway schist was uplifted, accompanied by fracturing in the zone of most intense bending; (e) At the same stage, the border zone between the gneiss and the surrounding schist was penetrated by particularly large amounts of solutions from which quartz, chlorite, magnetite, and sericitic muscovite were abundantly precipitated. Simultaneously, many of the previously formed metamorphic minerals, such as the garnet metacrysts in the schist, and hornblende in the gneiss complex, were chloritized in the vicinity of the dome border. The effect of these penetrating solutions faded gradually with increasing distance from the dome border.

(5) A long period of erosion lasted until the Pleistocene. As the gneiss complex came in contact with ground-water circulation and surface erosion, the dome was excavated into a topographic basin.

(6) Scouring by Pleistocene ice probably deepened the basin further. Subsequently, glacial till and late glacial outwash gravels were deposited in the interior of the basin, and, at present, modest post-Pleistocene erosion and creep begin to modify the glacial relief of the region.

It is tempting to suggest more definite correlations between the various orogenetic stages here outlined, and events in the Paleozoic history of other portions of New England. However, the writer feels that the available information for this region is too meager. Certainly the metamorphism and doming occurred after Conway time, and very probably the Conway formation is, at least in part, of Ordovician age. It seems probable to the writer that the Shelburne Falls gneiss complex is distinctly older than the Conway formation, but it should be pointed out that several gneiss domes, about 65 miles north-northeast of the region, in western New Hampshire (Chapman, 1942; Chapman, Billings, and Chapman, 1944), although structurally similar to the Shelburne Falls dome, are thought to be considerably younger. Again, the large Pelham gneiss dome, 20 miles east of Shelburne Falls (Balk, 1942), is very similar to the Shelburne Falls gneiss dome in some respects, but is surrounded by an entirely different series of crystalline schists which, in the writer's opinion, does not

allow as yet any correlation with the formations east of the axis of the Berkshire Hills.

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Manuscript Received by the Secretary of the Society, May 28, 1945.

EXPLANATION OF PLATES 5 AND 6

PLATE 5.—PHOTOMICROGRAPHS OF MICA SCHIST AND PORPHYRY DIKE

FIGURE

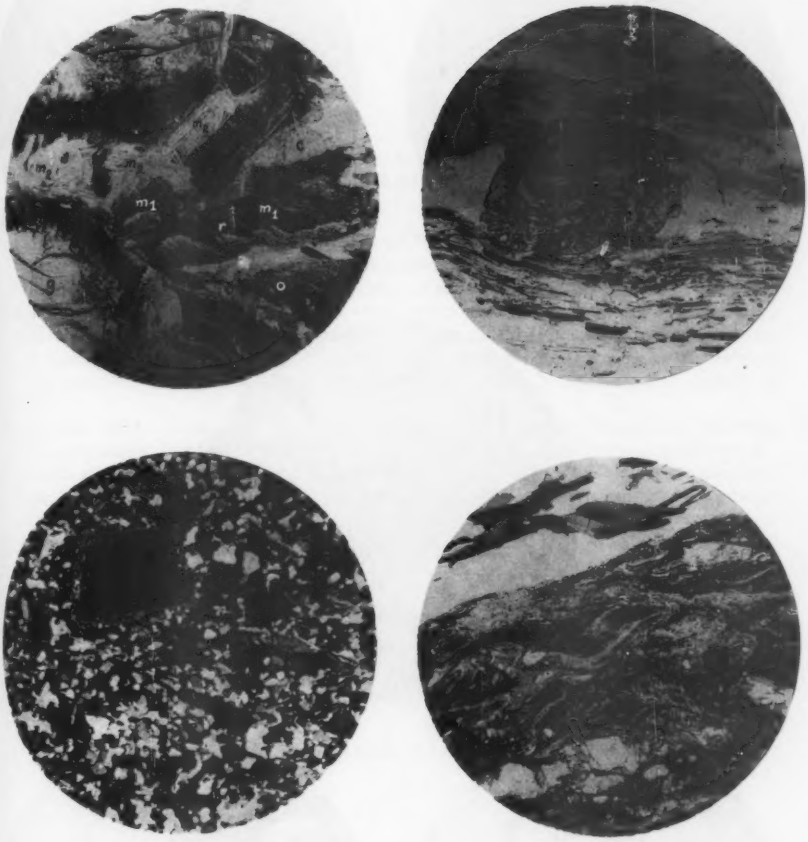
1.—Conway schist. Southwest slope of Pocumtuck Mountain, Heath quadrangle, Massachusetts. Plain polarized light. Right half is aggregate of dusty oligoclase (o) and early muscovite (m_1). Between 2 garnets (g) blades of late, clear, unbent muscovite (m_2); late, unbent chlorite (c) in upper right-hand corner; r: rutile.

2.—Conway schist with garnet metacryst. West shore of Deerfield River, due west of Rowe Lot Hill, Shelburne Falls quadrangle, Massachusetts. Plain polarized light. Note sigmoidal rows of quartz blebs in garnet, due to rotation of growing crystal. Groundmass of quartz, muscovite, and biotite.

3.—Quartz diorite porphyry Dike no. 2. Bed of Sluice Brook, south of U. S. highway no. 2, Shelburne Falls quadrangle, Massachusetts. Crossed nicols. Groundmass of oligoclase and quartz, with zoned oligoclase phenocryst.

4.—Deformed border of gneiss. In railroad cut, southwest shore of Deerfield River, 2½ miles southeast of Shelburne Falls, Shelburne Falls quadrangle, Massachusetts. Plain polarized light. Schistose, chloritized amphibolite on lower right. Wavy foliae enclose larger grains of quartz and epidote. Silicified Conway schist in upper left, with biotite (dark) and clear quartz (white).

Diameters of all fields: 3.3 millimeters



PHOTOMICROGRAPHS OF MICA SCHIST AND PORPHYRY DIKE

PHOTOMICROGRAPHS OF TOURMALINIZED DIKE, CHLORITIZED SCHIST, AND FOLDED AMPHIBOLITE

PLATE 6.—PHOTOMICROGRAPHS OF TOURMALINIZED DIKE, CHLORITIZED SCHIST, AND FOLDED AMPHIBOLITE

FIGURE

1.—Tourmalinized quartz diorite porphyry Dike no. 7. Southwest slope of High Ledge, Shelburne Falls quadrangle, Massachusetts. Plain polarized light. Poikiloblasts of tourmaline show prismatic cross-sections. White inclusions are oligoclase and quartz.

2.—Conway schist. Approximately 40 feet above gneiss contact, southwest slope of Pocumtuck Mountain, Heath quadrangle, Massachusetts. Plain polarized light. In right half, remnant of garnet (g), with chlorite shell (c) occupying most of the original metacryst. Surrounding the metacryst, aggregate of coarse, clear, unstrained quartz (q), muscovite (m), and biotite (b).

3.—Conway schist. Near northern border of gneiss dome, northwest of Pocumtuck Mountain, Heath quadrangle, Massachusetts. Plain polarized light. Large metacryst of chlorite (c), across original foliation (from upper left to lower right), and surrounding the remnant of a garnet metacryst (g); dusty oligoclase (ol) near center; quartz (q) and muscovite (m) in groundmass.

4.—Conway schist. Seven feet above gneiss contact, 2000 feet south of summit, Pocumtuck Mountain, Heath quadrangle, Massachusetts. Plain polarized light. Garnet metacryst (g) at bottom, with shell of chlorite (c) and quartz (q). Entire dusty zone extending from left to right is one oligoclase metacryst (ol). Quartz and muscovite aggregate in upper left hand quadrant.

5.—Amphibolitic injection gneiss. Near crest of Goodnow Mountain, Ashfield quadrangle, Massachusetts. Plain polarized light. Apex of a small fold is made up of straight, unbent prisms of hornblende, indicating precrystalline deformation of the rock.

Diameters of all fields: 3.3 millimeters

DO NOT COPY

amphibolite – gneissic qu

mixed zones; degree of darkness

abundance of dark minerals –. aplitic

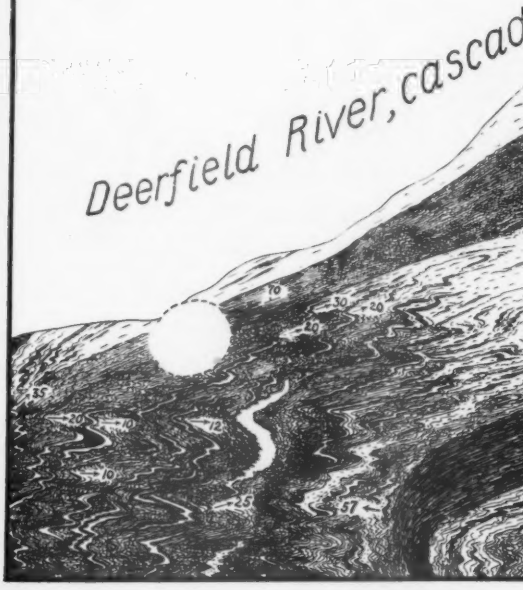
vein – edge of pothole; deep, wate

partly dry holes show geology at bottom –

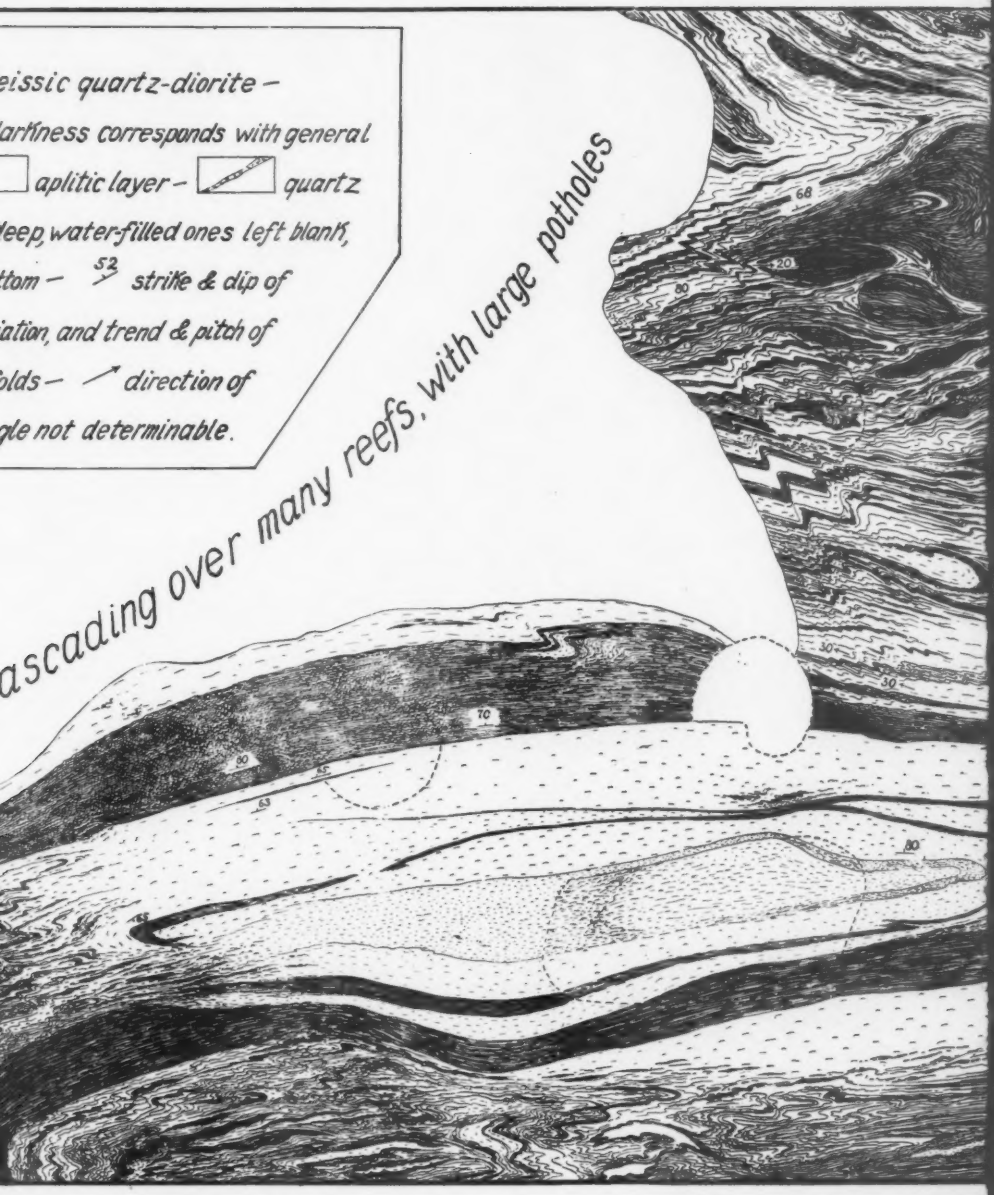
foliation – 32 15 strike & dip of foliation, and

lineation – 23 pitch of axes of folds –

pitch of axis known, but pitch angle not d



On north bank of Deerfield River, at Shel

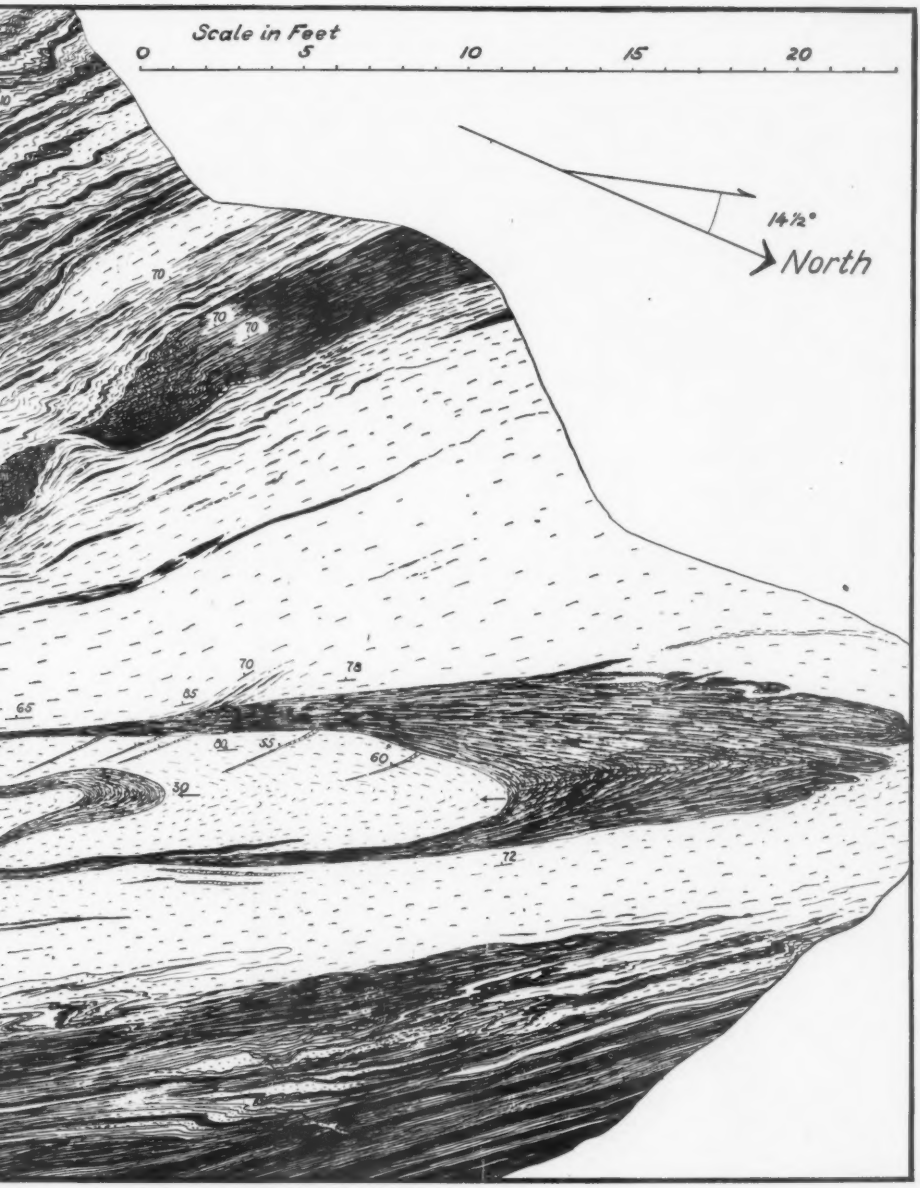


MAP OF FOLDED INJECTIO

er, at Shelburne Falls. Four isoclinally folded amphibolite layers are separated by zones of quartz di
near north end, in position of gash veins or tension crack

MAP OF FOLDED INJECTION GNEISS

hibolite layers are separated by zones of quartz diorite gneiss. Outer amphibolite layer sl
orth end, in position of gash veins or tension crack fillings near the apex of thefold.



lite layer shows minute crenulations at southwestern border, and five quartz veins
ld.

NEW HAMPSHIRE STATE PLANNING
AND DEVELOPMENT COMMISSION AND HIGHWAY DEPARTMENT

NEW HAMPSHIRE-VERMONT
BELLOWS FALLS QUADRANGLE

LEGEND

METAMORPHIC AND IGNEOUS ROCKS

MISSISSIPPIAN ? — *White Mountain Magma Series*

Camptonite
(Medium- to fine-grained, dark-gray camptonite composed of andesine-labradorite and brown hornblende. Locally it is porphyritic or amygdaloidal.)

LATE DEVONIAN ? — *New Hampshire Magma Series*

Pegmatite
(Strike and dip, or strike, given where known; plus sign indicates location only. No attempt has been made to show size, shape, and quality; some pegmatites are probably related to the Ollverian magma series.)

Granite
(Medium-grained, light-gray granite composed of albite-oligoclase, potash feldspar, muscovite, and biotite.)

Bethlehem gneiss
(Medium- to coarse-grained, gray granite to granodiorite gneiss, composed of oligoclase-andesine, potash feldspar, biotite, and muscovite.)

MIDDLE DEVONIAN ? — *Ollverian Magma Series*

Granite and quartz monzonite gneiss
(Fine- to medium-grained, pink granite to quartz monzonite gneiss, composed of oligoclase-andesine, potash feldspar, and biotite.)

LOWER DEVONIAN — *Lower Devonian*

Littleton formation
(Zone m: mica schist, mica-quartz schist, and quartz-mica schist, each with porphyroblasts of biotite, garnet, and staurolite; interbedded quartzite and quartz conglomerate (Dlq) ; interbedded lime-silicate granulite and schist (Dll) ; interbedded amphibolite and felsitic volcanics (Dlv) . Zone k: sillimanite schist, mica schist, mica-quartz schist, quartz-mica schist, and quartzite; interbedded quartzite and quartz conglomerate (Dlq) ; areas where concordant injections of Bethlehem gneiss are abundant. (Dll).

SILURIAN — *Lower or Middle*

Clough formation
(Zones m and k: Quartz conglomerate, quartzite, and quartz-mica schist.)

UNCONFORMITY

PRE-SILURIAN, PROBABLY ORDOVICIAN — *Upper Ordovician ?*

Partridge formation
(Zone m: mica schist, mica-quartz schist, quartz-mica schist, and thin quartzite, each with porphyroblasts of biotite and garnet. Zone k: mica schist, mica-quartz schist, quartz-mica schist, quartzite, and sillimanite schist.)

Ammonoosuc volcanics
(Zones m and k: amphibolite and some biotite gneiss.)

Lower part of Ammonoosuc volcanics, all of the Albee formation, and upper part of the Orfordville formation, which are present elsewhere, are missing in this quadrangle due to the Northey Hill thrust.

Middle Ordovician ?

Orfordville formation
(Zone l: slate and graphitic sericite schist (Ool) ; and interbedded volcanic rocks composed of chlorite schist (Oov) thin quartzite, each with porphyroblasts of biotite, garnet, and staurolite; interbedded Hardy Hill member, quartzite and quartz conglomerate (Oql) ; interbedded calcareous rocks, amphibolite and some biotite gneiss (Oov).

METAMORPHIC ZONES

Shown below formation symbol thus: Dl / m

l - low-grade
m - middle-grade
h - high-grade

CONTACTS

Accurate

Approximate and diagrammatic due to poor exposures.

Indefinite as sharp contact is lacking

The quartzite and quartz conglomerate Ooh, Sc, and Dlq are discontinuous; the isolated outcrops are connected by the dash-dot line to indicate the inferred location of the horizon where the stratigraphic unit is absent.

SPECIAL SYMBOLS

(Strike and dip symbols represent only a small percentage of the field observations.)

Strike and dip of bedding, including inverted and normal beds.

Strike of vertical beds.

Strike and dip of overturned beds.

Horizontal bedding.

Strike and dip of foliation and schistosity.

Strike of vertical foliation and schistosity.

Horizontal schistosity.

Normal fault; U on upthrown side.

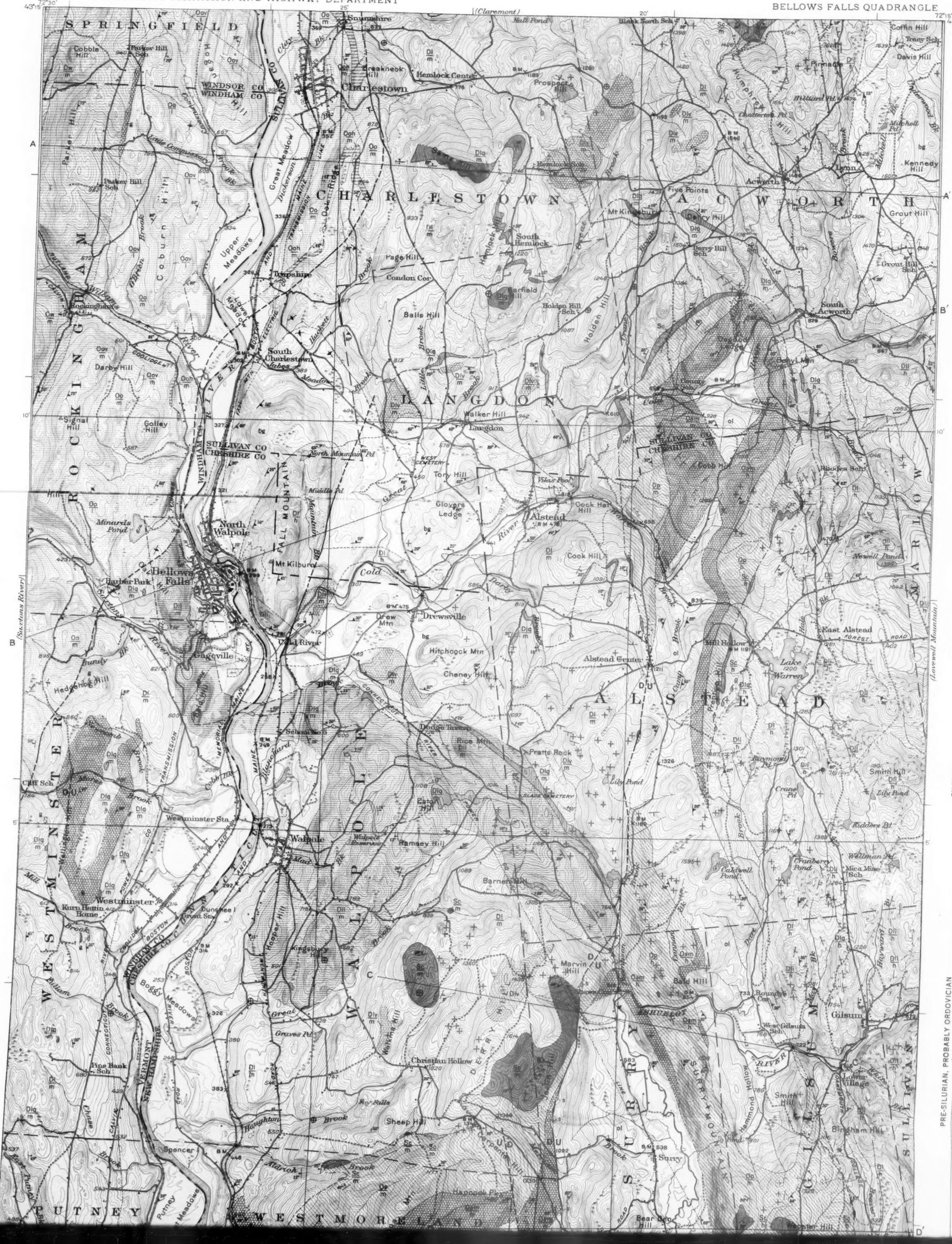
Thrust fault; T on upthrown side.

Silicified fault zone.

Mines, prospects, and quarries, mostly abandoned.

NEW HAMPSHIRE STATE PLANNING
AND DEVELOPMENT COMMISSION AND HIGHWAY DEPARTMENT

NEW HAMPSHIRE-VERMONT
BELLOWS FALLS QUADRANGLE



LEGEND

METAMORPHIC AND IGNEOUS ROCKS

MISSISSIPPIAN ? — White Mountain Magma Series

c — **Camptonite**
(Medium- to fine-grained, dark-gray camptonite composed of andesine-labradorite and brown hornblende. Locally it is porphyritic or amygdaloidal.)

LATE DEVONIAN ? — New Hampshire Magma Series

Pegmatite
(Strike and dip, or strike, given where known; plus sign indicates location only. No attempt has been made to give size, shape, and quality; some pegmatites are probably related to the Oliverian magma series.)

g — **Granite**
(Medium-grained, light-gray granite composed of albite-oligoclase, potash feldspar, muscovite, and biotite.)

bg — **Bethlehem gneiss**
(Medium- to coarse-grained, gray granite to granodiorite gneiss, composed of oligoclase-andesine, potash feldspar, biotite, and muscovite.)

MIDDLE DEVONIAN ? — Oliverian Magma Series

ol — **Granite and quartz monzonite gneiss**
(Fine- to medium-grained, pink granite to quartz monzonite gneiss, composed of oligoclase-andesine, potash feldspar, and biotite.)

LOWER DEVONIAN — Lower Devonian

Littleton formation
(Zone m: mica schist, mica-quartz schist, and quartz-mica schist, each with porphyroblasts of biotite, garnet, and staurolite; interbedded quartzite and quartz conglomerate (Dlq) ; interbedded lime-silicate granulite and schist (Dll) ; interbedded amphibolite and felsitic volcanics (Dlv). Zone h: sillimanite schist, mica schist, mica-quartz schist, quartz-mica schist, and quartzite; interbedded quartzite and quartz conglomerate (Dlq) ; areas where concordant injections of Bethlehem gneiss are abundant. (Dll).

SILURIAN — Lower or Middle

Sc — **Clough formation**
(Zones m and h: Quartz conglomerate, quartzite, and quartz-mica schist.)

UNCONFORMITY

PRE-SILURIAN, PROBABLY ORDOVICIAN — Upper Ordovician ?

Op — **Partridge formation**
(Zone m: mica schist, mica-quartz schist, quartz-mica schist, and thin quartzite, each with porphyroblasts of biotite and garnet. Zone h: mica schist, mica-quartz schist, quartz-mica schist, quartzite, and sillimanite schist.)

Oam — **Ammonoosuc volcanics**
(Zones m and h: amphibolite and some biotite gneiss.)

Lower part of Ammonoosuc volcanics, all of the Albee formation, and upper part of the Orfordville formation, which are present elsewhere, are missing in this quadrangle due to the Northey Hill thrust.

Middle Ordovician ?

Oam / Oo / Oov — **Orfordville formation**
(Zone l: slate and graphitic sericite schist (Oo) ; and interbedded volcanic rocks composed of chlorite schist (Oov) ; Zone m: graphitic mica schist, mica schist, and paraschist, and staurolite; interbedded Hardy Hill member, quartzite and quartz conglomerate (Oo) ; interbedded volcanic rocks, amphibolite and some biotite gneiss (Oov).

Ow

METAMORPHIC ZONES

Shown below formation symbol thus: Dl / m

l - low-grade
m - middle-grade
h - high-grade

CONTACTS

Accurate

Approximate and diagrammatic due to poor exposures.

Indefinite as sharp contact is lacking

The quartzite and quartz conglomerate Ooh, Sc, and Dlq are discontinuous; the isolated outcrops are connected by the dash-dot line to indicate the inferred location of the horizon where the stratigraphic unit is absent.

SPECIAL SYMBOLS

(Strike and dip symbols represent only a small percentage of the field observations.)

Strike and dip of bedding, including inverted and normal beds.

Strike of vertical beds.

Strike and dip of overturned beds.

Horizontal bedding.

Strike and dip of foliation and schistosity.

Strike of vertical foliation and schistosity.

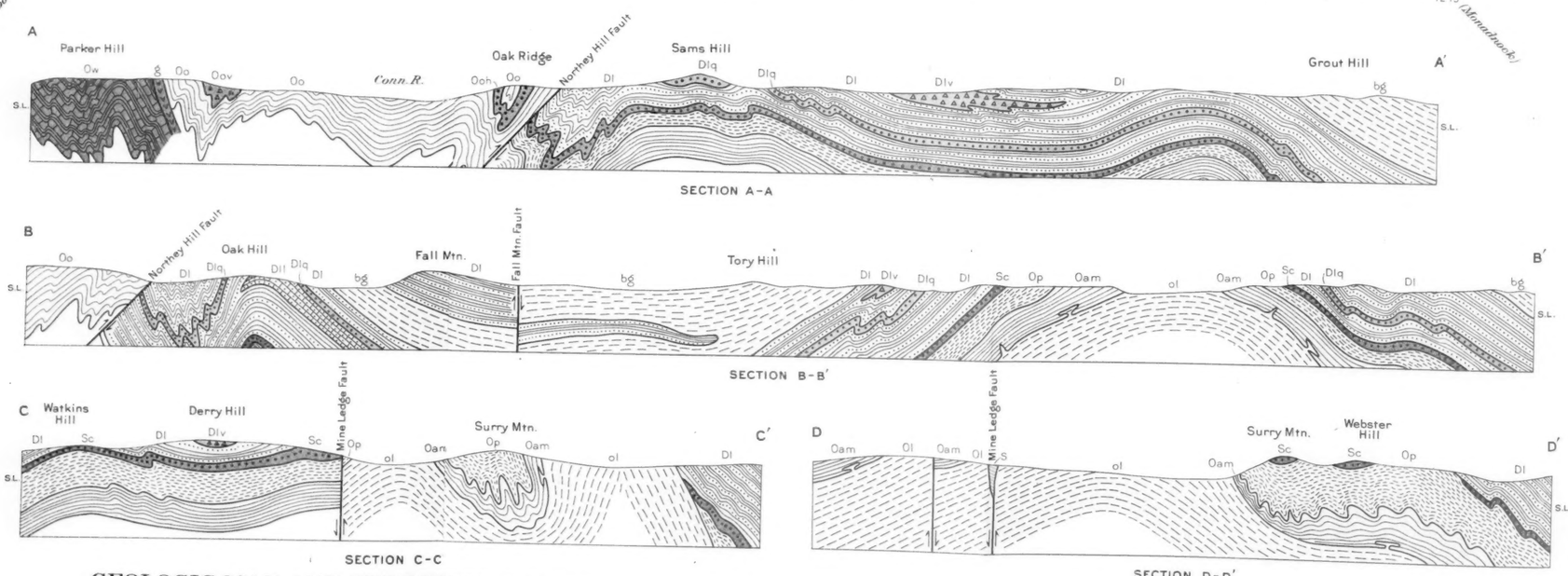
Horizontal schistosity.

Normal fault; U on upthrown side.

Thrust fault; T on upthrown side.

Silicified fault zone.

Mines, prospects, and quarries, mostly abandoned.



GEOLOGIC MAP AND STRUCTURE SECTIONS OF THE BELLOWS FALLS QUADRANGLE, NEW HAMPSHIRE

Topographic base by U. S. Geological Survey, surveyed in cooperation with the State of New Hampshire.

Scale 62 500

1 0 1 2 3 4 Miles

5000 0 5000 10000 15000 20000 Feet

1 0 1 2 3 4 5 Kilometers

Contour interval 20 feet

Datum is mean sea level.

Geology by F. C. Kruger, assisted by J. H. Todd, G. C. Kennedy, J. H. Eric, G. E. Moore, and W. R. Thurston. Directed by Marland P. Billings. Geology surveyed 1937-1940, with the aid of grants from the Sayles Fund and Shaler Fund of Harvard University. Published 1945. Oriented pegmatite data from G. W. Stewart, U. S. Geological Survey.

MIDDLE DEVONIAN

Ow

Waits River formation

(Zone m: mica-quartz schist, calcareous mica-quartz schist, each with porphyroblasts of biotite and garnet; also impure marble.)

LOWER DEVONIAN

Lower Devonian

Littleton formation

(Zone m: mica schist, mica-quartz schist, and quartz-mica schist, each with porphyroblasts of biotite, garnet, and staurolite; interbedded quartzite and quartz conglomerate (Dlq) ; interbedded lime-silicate granulite and schist (Dll) ; interbedded amphibolite and felsitic volcanics (Dlv) . Zone h: sillimanite schist, mica schist, mica-quartz schist, quartz-mica schist, and quartzite; interbedded quartzite and quartz conglomerate (Dlq) ; areas where concordant injections of Bethlehem gneiss are abundant.(Dll).

SILURIAN

Lower or Middle

Sc

Clough formation

(Zones m and h: Quartz conglomerate, quartzite, and quartz-mica schist.)

UNCONFORMITY

PRE-SILURIAN, PROBABLY ORDOVICIAN

Upper Ordovician ?

Op

Partridge formation

(Zone m: mica schist, mica-quartz schist, quartz-mica schist, and thin quartzite, each with porphyroblasts of biotite and garnet. Zone h: mica schist, mica-quartz schist, quartz-mica schist, quartzite, and sillimanite schist.)

Oam

Ammonoosuc volcanics

(Zones m and h: amphibolite and some biotite gneiss.)

Lower part of Ammonoosuc volcanics, all of the Albee formation, and upper part of the Orfordville formation, which are present elsewhere, are missing in this quadrangle due to the Northey Hill thrust.

Middle Ordovician ?

Oph

Oo

Oov

Orfordville formation

(Zone l: slate and graphitic sericite schist (Oo) ; and interbedded volcanic rocks composed of chlorite schist (Oov) Zone m: graphitic mica schist, mica schist, and paper-thin quartzite, each with porphyroblasts of biotite, garnet, and staurolite; interbedded Hardy Hill member, quartzite and quartz conglomerate (Oph) ; interbedded volcanic rocks, amphibolite and some biotite gneiss (Oov).

Strike and dip of overturned bed.

Horizontal bedding.

Strike and dip of foliation and schistosity.

Strike of vertical foliation and schistosity.

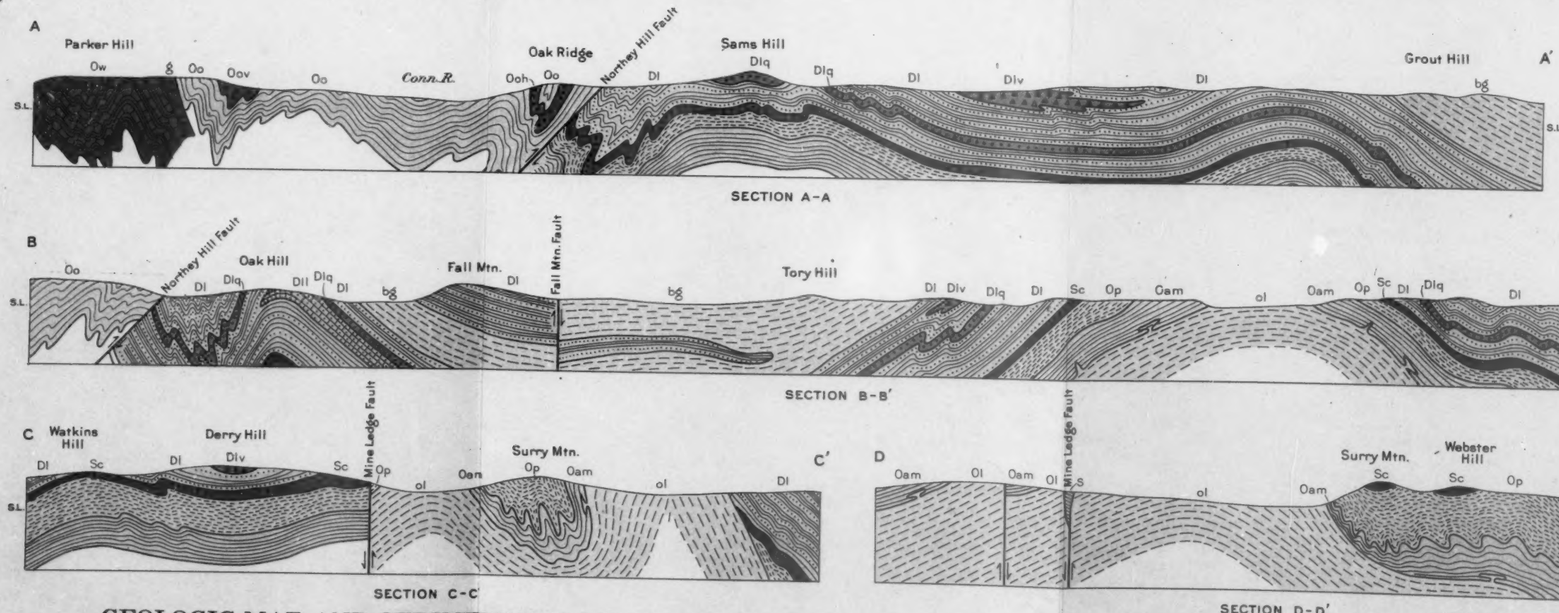
Horizontal schistosity.

Normal fault; U on upthrown side.

Thrust fault; T on upthrown side.

Silicified fault zone.

Mines, prospects, and quarries, mostly abandoned.



GEOLOGIC MAP AND STRUCTURE SECTIONS OF THE BELLOWS FALLS QUADRANGLE, NEW HAMPSHIRE

Topographic base by U. S. Geological Survey, surveyed in cooperation with the State of New Hampshire.

Scale 62500

Contour interval 20 feet

Datum is mean sea level

Geology by F. C. Kruger, assisted by J. H. Todd, G. C. Kennedy, J. H. Eric, G. E. Moore, and W. R. Thurston. Directed by Marland P. Billings. Geology surveyed 1937-1940, with the aid of grants from the Sayles Fund and Shaler Fund of Harvard University. Published 1945.
Oriented pegmatite data from G. W. Stewart, U. S. Geological Survey.

MIDDLE DEVONIAN

(Zone n: gneiss, garnet, and biotite.)

LOWER DEVONIAN — *Lower Devonian*

Littleton formation

(Zone m: mica schist, mica-quartz schist, and quartz-mica schist, each with porphyroblasts of biotite, garnet, and staurolite; interbedded quartzite and quartz conglomerate (Dlq) ; interbedded amphibolite and felsitic volcanics (Dlv) . Zone k: sillimanite schist, mica schist, mica-quartz schist, quartz-mica schist, and quartzite; interbedded quartzite and quartz conglomerate (Dlq) ; areas where concordant injections of Bethlehem gneiss are abundant.(Dll).

SILURIAN — *Lower or Middle*

Clough formation

(Zones m and k: Quartz conglomerate, quartzite, and quartz-mica schist.)

UNCONFORMITY

PRE-SILURIAN, PROBABLY ORDOVICIAN — *Upper Ordovician ?*

Partridge formation

(Zone m: mica schist, mica-quartz schist, quartz-mica schist, and thin quartzite, each with porphyroblasts of biotite and garnet. Zone k: mica schist, mica-quartz schist, quartz-mica schist, quartzite, and sillimanite schist.)

Ammonoosuc volcanics

(Zones m and k: amphibolite and some biotite gneiss.)

Lower part of Ammonoosuc volcanics, all of the Albee formation, and upper part of the Orfordville formation, which are present elsewhere, are missing in this quadrangle due to the Northey Hill thrust.

Middle Ordovician ?

Orfordville formation

(Zone l: slate and graphitic sericite schist (Oo) ; and interbedded volcanic rocks composed of chlorite schist(Oov) Zone m: graphitic mica schist, mica schist, and paper-thin quartzite, each with porphyroblasts of biotite, garnet, and staurolite; interbedded Hardy Hill member, quartzite and quartz conglomerate(Ooh) ; interbedded volcanic rocks, amphibolite and some biotite gneiss(Oov).

Waits River formation

(Zone m: mica-quartz schist, calcareous mica-quartz schist, each with porphyroblasts of biotite and garnet; also impure marble.)

Strike and dip of foliation

⊕ Horizontal bedding.

Strike and dip of foliation and schistosity.

Strike of vertical foliation and schistosity.

Horizontal schistosity.

Normal fault; U on upthrown side.

Thrust fault; T on upthrown side.

Silicified fault zone.

Mines, prospects, and quarries, mostly abandoned.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 57, PP. 161-206, 2 PLS., 7 FIGS. FEBRUARY 1946

STRUCTURE AND METAMORPHISM OF THE BELLOWS FALLS QUADRANGLE OF NEW HAMPSHIRE AND VERMONT

BY FREDRICK C. KRUGER

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ABSTRACT

The most common rocks in the Bellows Falls quadrangle of southwestern New Hampshire and adjacent Vermont are metamorphic, having been derived from sedimentary and volcanic formations that range in age from middle Ordovician (?) to lower Devonian. Although middle-grade metamorphism is characteristic of most of the quadrangle, a zone of high-grade metamorphism occurs along the east margin of the region, and areas of low-grade metamorphism occur in the northwest portion of the quadrangle. It is thus possible to study within one quadrangle all three grades of metamorphism. The metamorphism was dynamothermal, and there was no appreciable addition of material. The chemical composition of isomorphous minerals, such as plagioclase and biotite, depends upon both the composition of the original rock and the grade of metamorphism.

In general, the lithology of the stratified rocks is not radically different from that to the north in previously mapped regions. But in the Devonian Littleton formation two white quartzite members and associated lime-silicate rocks appear, the latter derived from impure dolomites.

The principal folding is Acadian (late Devonian) and produced structural features that trend northeast-southwest. The Bronson Hill anticline, a major fold that can be traced 150 miles in New Hampshire, trends north-south a few miles east of the center of the quadrangle. West of this is the Walpole syncline, a broad open fold that is 6 miles across and is characterized by relatively gentle dips ranging from zero to 45 degrees. This syncline is complicated by a series of "cross folds" which trend west-northwesterly and are several miles in wave length. The northwest portion of the quadrangle is occupied by the steeply dipping west limb of the Charlestown syncline. In general, schistosity and bedding are parallel.

The Northey Hill thrust, a major fault that can be traced for at least 100 miles in western New Hampshire, separates the Walpole and Charlestown synclines from one another. It is pre-metamorphism and is now a high-angle fault along which the stratigraphic throw is approximately 10,000 feet. Four normal faults are of sufficient magnitude to show on the geological map. They trend north-south, and the stratigraphic throw along some of them exceeds 1000 feet.

As elsewhere in New Hampshire, the intrusion of thick concordant plutons was associated with the Acadian orogeny. A body of the Oliverian magma series was injected as a concordant sheet into the Ordovician (?) Ammonoosuc volcanics; probably originally horizontal, it is now exposed in the center of several north-trending anticlines developed subsequent to its intrusion. A body of Bethlehem gneiss was injected as a concordant sheet into the Devonian Littleton formation, probably during the last stages of the folding. Subsequent erosion has unroofed this body and isolated a western portion from the main pluton 6 miles to the east. Small bodies of granite intrude the schists with cross-cutting relations.

INTRODUCTION

Recently geological mapping in western New Hampshire has been extended west, northeast, and south from the fossil localities at Littleton. The Bellows Falls quadrangle on the Connecticut River is in the southwestern part of the area covered by this modern mapping (Fig. 1). Pioneer studies of the bedrock geology were made by C. T. Jackson (1844), E. Hitchcock (1861), C. H. Hitchcock (1874; 1877; 1878), and C. H. Richardson (1931a; 1931b; 1933a; 1933b). The region presents problems in crystalline rocks, rock-defended terraces and meander scars (Davis, 1909), and glacial drainage phenomena (Lougee, 1935; 1939). Although the present investiga-

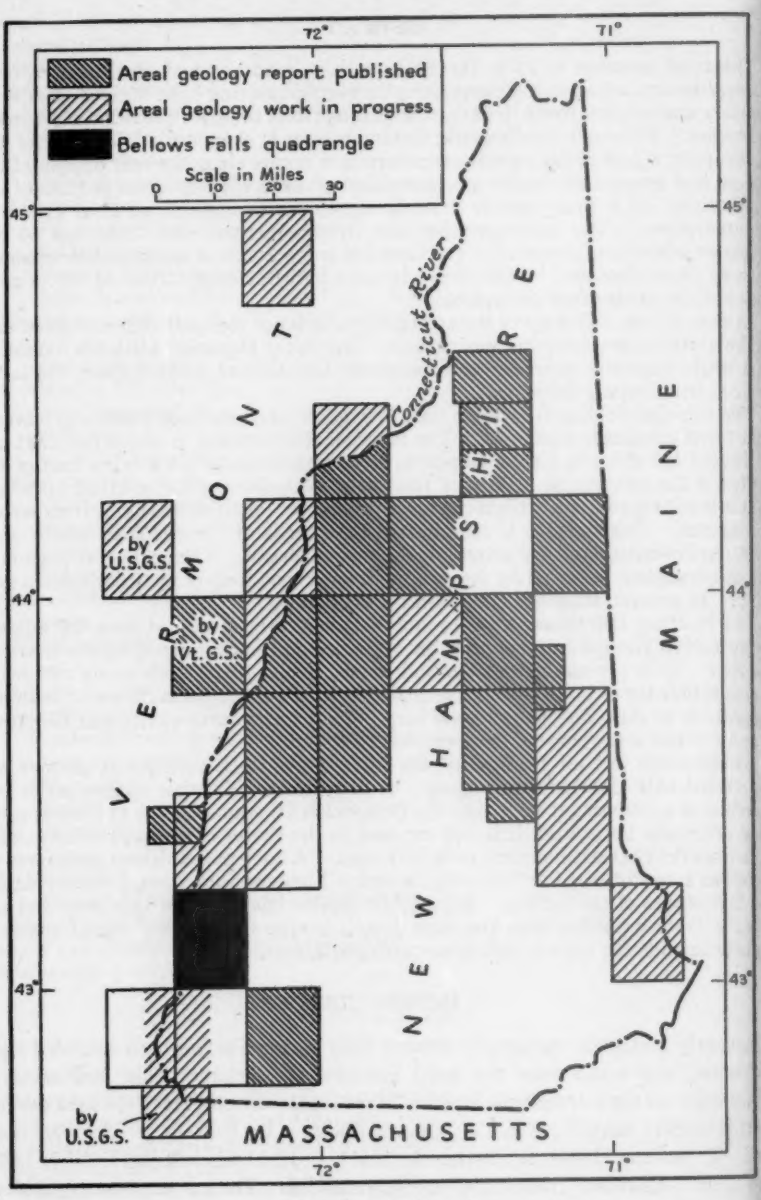

FIGURE 1.—*Index map*

Bellows Falls quadrangle and recently mapped areas

tions are mainly in structural, stratigraphic, and metamorphic geology, the physiographic and glacial geology were included in the study but will not be discussed in this paper.

The field work was completed during the summers of 1937 through 1940. Able assistance was accorded by J. H. Todd, G. C. Kennedy, J. H. Eric, G. E. Moore, and W. R. Thurston. Valuable counsel in the field was received from Professor Marland P. Billings. Inestimable aid was given by both Professor Marland P. Billings and Professor Esper S. Larsen in the course of laboratory studies and during the preparation of this paper. Grateful acknowledgment is made to the Associates in Science and to the Holden Fund of Harvard University for generous grants to help finance the field work and the cost of thin sections.

Compass and barometer traverses were plotted on photostatic copies of the 1930 topographic map enlarged to 3 inches to the mile. Wherever it was advantageous to use a scale of 6 or 9 inches to the mile, the 100-foot contours were copied and enlarged by hand. This procedure was convenient where outcrops were numerous, the country open, and locations easy. Pace and compass maps were commonly employed where the complexity of the structure or the difficulty of location warranted their use. Sketches on all scales, regional to microscopic, were made. Measurements of the plunge of lineation or folds involving the interrelated readings of the strike and dip of a plane and a line lying in that plane were checked in the field on correction curves similar to those which were later published by C. A. and R. W. Chapman (1939). This immediate check at the outcrop permitted retaking of the least reliable recordings. In the course of mapping, approximately 15,000 compass and clinometer readings were recorded. In the field about 600 specimens were collected from which 116 thin sections were prepared and studied.

GENERAL LITHOLOGICAL FEATURES

The original sedimentary and volcanic rocks, occupying more than half of the Bellows Falls quadrangle, have undergone regional metamorphism. The grade of metamorphism ranges from low grade in places along the Connecticut River to high grade in the eastern part of the quadrangle (Fig. 2).

The low-grade zone is characterized by albite, chlorite, epidote, and sericite. In the middle-grade zone such minerals as biotite, garnet, hornblende, diopside, staurolite, and intermediate plagioclase, all of which are absent in the low-grade zone, are typical. Sillimanite occurs only in the high-grade zone. The rocks range in age from middle Ordovician (?) to lower Devonian. Though no fossils have been found in this area the correlations have been made with recognizable horizons traced from the previously mapped quadrangles. Although some of the lithological types have changed character along the strike, and others have appeared, and yet others have disappeared, the bulk of the stratigraphic column retains the major features as described by Billings (1937). The igneous rocks belong to the same magma series as those occurring elsewhere in western New Hampshire.

The columnar section for the Bellows Falls area is given in Figure 3. The problem of correlation is discussed after the discription of all the formations, because in this way a more comprehensive treatment is possible.

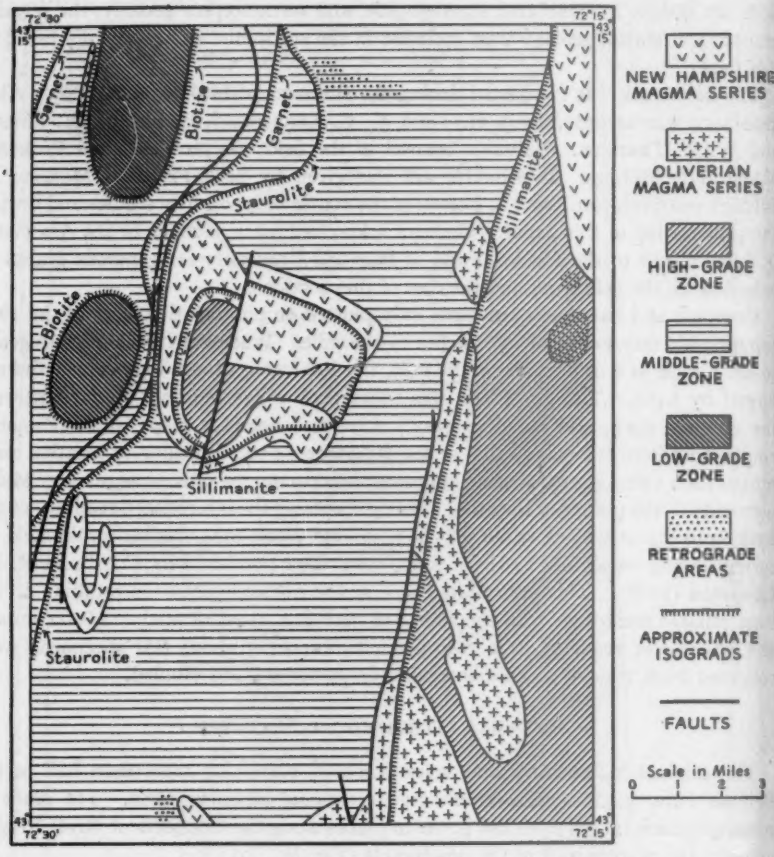

FIGURE 2.—*Metamorphic zones in the Bellows Falls quadrangle*

Approximate isograds show progressive increase in metamorphism toward southeast and northwest

ORDOVICIAN (?) STRATA

GENERAL STATEMENT

In the Bellows Falls quadrangle the Ordovician (?) strata include the Waits River formation, the Orfordville formation, the Ammonoosuc volcanics, and the Partridge formation (Pl. 1). The Albee formation, normally present between the Orfordville and Ammonoosuc formations, is absent due to faulting.

WAITS RIVER FORMATION

Part of the Waits River formation occupies the northwest corner of the quadrangle, where sections of it are well exposed on Cobble Hill and along the tracks of the Rutland Railroad northwest of the village of Rockingham.

All of these rocks belong to the middle-grade zone of metamorphism. Characteristically the outcrops are deeply etched by weathering which reveals the intricacies of the minor folds. On the hilltops a small-scale trellised drainage results from the interbedding of soluble calcareous rocks with more resistant schists. This feature is clearly visible where the veneer of glacial till is not too thick to disguise the form of the bedrock surface. Where the calcareous schists have been thoroughly leached, yet erosion has been slight, only the porous limonite-stained skeleton composed of silicate impurities remains.

The rocks of the Waits River formation are medium- to coarse-grained, dark-gray calcite-mica-quartz schists[1] which contain ¼- to 1-inch beds of gray quartzite and lenses of dark-gray impure marble as much as several feet thick. Their unmetamorphosed equivalents were argillaceous limestones, sandstones, and impure limestones. The schists possess a marked axial-plane schistosity, but the micas near the competent quartzite layers tend to follow the bedding around the noses of folds. On Cobble Hill in Springfield township porphyroblasts of garnet and hornblende in a calcite-quartz schist attain diameters of 2 inches. These coarse porphyroblasts give the rock the appearance of a conglomerate, thus contributing to the name of the hill.

Modes estimated from thin sections of the Waits River formation appear in Table 1, columns 1 to 3. The essential minerals are quartz, calcite, and biotite; accessories are magnetite, graphite, and apatite. Nearly all fresh specimens contain enough carbonate to react with acid. With the exception of one coarse-textured belt in the Waits River formation, the minerals in the groundmass average 0.1 to 0.5 millimeter in diameter. The schistose structure results chiefly from the biotite and chlorite. The micaceous minerals are intergrown feathery flakes which are difficult to separate for study. Muscovite is scarce. The refractive index and specific gravity indicate that the garnets of the Waits River formation are probably almandite-spessartite with a small amount of lime.

The repetition due to folding makes measurement of the thickness of the portion of the Waits River formation within the Bellows Falls quadrangle uncertain. A fair estimate would be 2000± feet.

ORFORDVILLE FORMATION

General statement.—The Orfordville formation of the Bellows Falls quadrangle consists of a lower mica-quartz schist, an intermediate portion containing lenses of volcanics, and an upper black schist which contains the discontinuous Hardy Hill quartzite. The metamorphism is low-grade in some parts of the formation but elsewhere is middle-grade.

Black schist.—The black schist extends south from Charlestown to the west side of the quadrangle near Hedgehog Hill. Excellent exposures may be seen along the highway north of Bellows Falls on the Vermont side of the Connecticut River.

The rocks are constant in character and for the most part are light-gray to black sericitic schists and phyllites, but there is some sericite-quartz schist. The black

[1] For convenience metamorphic rocks are classified as follows: mica schist, less than 60 per cent quartz plus feldspar; mica-quartz schist, from 60 to 80 per cent quartz plus feldspar; quartz-mica schist and quartzite, over 80 per cent quartz plus feldspar.

color is due to varying amounts of graphite, up to a few per cent. Axial plane schistosity is well developed in the aluminous rocks, but in more quartzitic layers the schistosity is parallel to the bedding. These schists probably represent metamorphosed black shales in which all of the primary features except bedding have been destroyed.

Modes estimated from thin sections appear in Table 1, columns 7 to 10. These schists are fine-grained. Minute porphyroblasts 0.5 to 1.5 millimeters in diameter, consisting of garnet, staurolite, and biotite, indicate middle-grade metamorphism and are common. Isolated areas of nonporphyroblastic sericite schist, sericite-chlorite schist, and slate of low-grade metamorphic character which are erratic in size and distribution are generalized on Figure 2. The low-grade rocks appear to be richer in both graphite and sulfides than the middle-grade rocks.

Oligoclase, in small amounts, is the only feldspar in the black schists. The micaceous minerals are so small that no optical data could be obtained. The garnets are probably almandite, as indicated by the refractive index and the specific gravity. Complete chloritization of garnets was observed in some specimens. Lines of poikiloblastic inclusions of quartz and magnetite contained within the garnet probably represent original bedding. These inclusions show that the porphyroblasts have been rotated from 15 to 70 degrees.

Hardy Hill quartzite.—The Hardy Hill quartzite is a resistant horizon within the black schists. It enters the quadrangle on the north at Snumshire and forms the tops of Breakneck Hill and Oak Ridge in Charlestown township. To the south the Hardy Hill quartzite crosses the Connecticut River and becomes very discontinuous. It crops out, however, at the north end of the highway bridge across the Williams River. The discontinuity is due to irregular deposition, to tectonic thinning and breaking, and to paucity of outcrops in covered areas. In areas intervening between discontinuous outcrops the horizon of the Hardy Hill quartzite is shown on the geological map by a dash-dot line. It is best exposed at its maximum thickness on the ridge northeast of Trapshire.

This member consists of white thin- to thick-bedded quartz conglomerate and quartzite. The bedding is indistinct because of thorough recrystallization, but schistosity even in the pure quartzites is marked by muscovite flakes which possess the same lineation as the ellipsoidal pebbles of vein quartz. The original sandstone and quartz-pebble conglomerate were extremely pure, containing only minor amounts of argillaceous material. The mineral composition of a pebble is shown by the mode in Table 1, column 11.

Volcanics.—A discontinuous band of volcanics crosses Hogan Hill and Coburn Hill in the northern part of Rockingham township, and extends a mile south of Williams River. This member consists chiefly of light-colored, fine-grained biotite-oligoclase schist and siliceous tuffs with lenses of massive medium- to coarse-grained chloritized amphibolite. In addition, metamorphosed sediments are represented by greenish-gray chlorite-epidote schist and dark-gray phyllite. Indefinite pillow structure was observed at one locality. The metamorphism is low-grade in some parts of the area, but is middle-grade elsewhere.

Table 1, columns 4 to 6, gives the estimated mineral composition of these rocks.

Quartz, andesine, biotite, chlorite, and hornblende make up the groundmass which ranges in size from 0.01 to 0.40 millimeter. Broken phenocrysts of subhedral plagioclase are from 0.1 to 0.7 millimeter in diameter. Octahedra of magnetite and cubes of pyrite occur as metacrysts especially in the phyllites and slates. The cross-micas are green biotite and chloritized biotite. According to the optical properties the biotite is probably of intermediate composition. The chlorite is optically positive ripidolite. Basal sections of the hornblende show a zoning, due to alteration and inclusions, parallel to the cleavages. This hornblende contains a considerable amount of pargasite.

Lower schist member.—The mica-quartz schists and dark-gray argillaceous quartzites that lie beneath the volcanics of the Ordordville formation and above the Waits River formation resemble the Brock Hill member of the Waits River formation of the Woodsville quadrangle (W. S. White, personal communication, 1941). In the Bellows Falls area there seems to be a complete transition stratigraphically downward from the Orfordville formation through the Brock Hill member to the Waits River formation. Because of the distance intervening between the Woodsville and the Bellows Falls quadrangles, no definite correlation is proposed, and rocks of Brock Hill lithology are mapped as a lower schist member of the Ordordville formation.

Thickness.—The thickness of the Orfordville formation is doubly uncertain because the upper contact is a thrust fault, and the small-scale folding is complex. An estimate for the portion exposed in the Bellows Falls quadrangle is 4000± feet, the upper part being black schist and the lower part volcanics and mica-quartz schist. The Hardy Hill quartzite member reaches 200 feet in thickness but is locally absent. The amount of black schist above the quartzite is variable. The average thickness is 1000± feet, but in places it is completely cut out by the Northey Hill fault, notably west of Sams Hill, Charlestown township. The thickness of the members of the Orfordville formation is comparable with that found elsewhere by others.

AMMONOOSUC VOLCANICS

The Ammonoosuc volcanics crop out adjacent to the Oliverian magma series in a belt extending south from the southwestern part of Acworth township, in the northeast corner of the quadrangle, to the south edge of the quadrangle. Excellent sections of the formation may be studied at Osgood Ledge in Acworth township and on Hancock Peak in Westmoreland township. The Ammonoosuc volcanics are banded light- and dark-colored, medium- to coarse-grained metamorphosed volcanic tuffs and breccias. Biotite gneiss with ¼-inch knots of milky quartz comprises the small felsic portion of the formation. The dominant rock is interbedded amphibolite in layers ¼ to 1 inch thick. Lenticular masses, probably original volcanic bombs and breccia fragments, may be seen, notably on the north face of Beryl Mtn. in Acworth township. In the banded rocks bedding is conspicuous, but in the homogeneous rocks the most outstanding structure is the schistosity. The amphibole crystals are oriented in a plane in conspicuous rosettes 2 inches in diameter.

Modes in Table 1, columns 12 to 14, show the chief constituents. The essential minerals are quartz, microcline, oligoclase-andesine, biotite, chlorite, and hornblende. Minor accessories include magnetite, sphene, apatite, green tourmaline, zircon, and

TABLE 1.—*Estimated modes of Ordovician (?) formations*

	Waits River Formation			Orfordville Formation							Ammonoosuc Volcanics			Partridge Formation			
				Volcanics			Schists			Hardy Hill Quartzite							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Porphyroblasts:																		
Amphibole			2															
Pyrite							tr											
Magnetite				10														
Biotite			3		tr				8						5	5		
Garnet	1		13	15			1	tr	6	10				1	1	5		7
Staurolite								tr	3	7								
Muscovite																5	2	
Sillimanite																	15	2
Phenocrysts:																		
Quartz				10														
Plagioclase				5		2												
Groundmass:																		
Quartz	}	33	}	20	}	}	59	}	}	21	98	}	31	25	50	30	35	}
Potash feldspar	48		44	20	36	85	18	37	19	20		49	10	20	25	10	30	60
Plagioclase	}		}	}	}	}	}	}	}	}		}	35	25	}	5	5	}
Muscovite**	30	1	2	tr	1	11	17	54	60	tr	2			12	15	15		20
Biotite	20			20	14		2	5		42	tr			5		25	8	10
Chlorite	1		4		9	1	3	2	3					10	4		5	tr
Pyrite					tr				1									
Magnetite			2									1	1				tr	1
Carbon			3		1		tr	tr	tr	tr								
Limonite	tr						tr				tr							
Leucoxene	tr						tr	tr							tr			

Limonite																			
Leucoxene	tr						tr	tr							tr				

Amphibole					33							50	23						
Sphene														tr					
Calcite		65	25		1			tr						1					
Zircon						tr								tr	tr	tr	tr	tr	tr
Apatite			2									tr	tr	tr					
Zoisite*		1	tr		5	1		tr							tr				tr
Tourmaline										tr				1	tr	tr			
Texture†	S	G	G	S	S	G	S	S	S	S	G	G-S	G-S	S	S	S	G	S	
Size of porphyroblasts in mm			1.00–2.50	0.01–0.80	0.70			0.50–0.70	1.00	0.70–1.50				0.50–1.00	0.50–1.50	0.20–1.50	6.00	5.00	
Size of phenocrysts in mm				0.20		0.10–0.70													
Size of groundmass in mm	0.10–0.50	0.20–0.40	0.01–0.20	0.01–0.02	0.01–0.40	0.05–0.10	0.02–0.20	0.01–0.40	0.20	0.02–0.20	0.20–1.00	0.10–0.30	0.10–0.50	0.10–0.40	0.10–0.30	0.05–0.80	0.50–1.00	0.40–0.80	

* Including epidote and allanite.
** Including sericite.
† S = schistose, G = granoblastic.

1. Fissile calcite-mica-quartz schist from which calcite has been leached.
2. Arenaceous marble.
3. Garnet-hornblende-calcite-quartz schist.
4. Garnet-biotite-feldspar schist.
5. Thin-banded amphibole-biotite schist (average of 2 thin sections).
6. Aphanitic banded siliceous volcanic tuff.
7. Sericite-quartz schist (average of 2 thin sections).
8. Sericite schist (average of 4 thin sections).
9. Staurolite-garnet-sericite schist (average of 2 thin sections).
10. Garnet-staurolite-biotite schist.
11. Pebble from quartz conglomerate.
12. Amphibole schist injected by granite gneiss.
13. Thin-banded light and dark amphibolite volcanics (average of 2 thin sections).
14. Garnet-biotite-muscovite schist.
15. Banded mica schist.
16. Garnet-muscovite-biotite schist.
17. Sillimanite gneiss.
18. Sillimanite-garnet-muscovite schist.

calcite. The grain size of the Ammonoosuc volcanics averages 0.1 to 0.5 millimeter, and porphyroblasts average 1.0 millimeter in diameter.

The red-brown biotite is of intermediate composition. The properties of the hornblende are variable because of alteration which may be seen around the edges of basal sections. The average amphibole has similar properties to those described by Chapman (1939, p. 137) and to an analyzed amphibole described by Billings (1937, p. 513).

The thickness of the Ammonoosuc volcanics exposed in the Bellows Falls quadrangle ranges from 500± to 2000± feet, this figure being variable because the lower contact is intrusive. Moreover, the portion below the horizon of intrusion of the Oliverian magma series is concealed.

PARTRIDGE FORMATION

The Partridge formation crops out in the same area as the Ammonoosuc volcanics. The rocks are schist and quartzite, characterized by middle-grade metamorphism in some places and by high-grade metamorphism elsewhere. Middle-grade rocks of the Partridge formation are well displayed on Gilboa Mtn. in Westmoreland township. Rocks of the high-grade zone occur east of the outcrops of the Oliverian magma series, and an especially good section may be seen on the west slope of Prentice Hill in Alstead township.

In the middle-grade zone the formation consists of medium-grained light- to dark-gray mica schist, mica-quartz schist, and paper-thin impure quartzite containing small garnet and biotite porphyroblasts. The high-grade equivalents, which are coarse muscovite-biotite schist and muscovite-quartz schist, contain garnet and sillimanite porphyroblasts. In general, the original sediments were arenaceous shales and sandstones. Some massive quartzitic horizons are highly garnetiferous and probably represent original impure arenaceous dolomites. Schistosity is well developed in the Partridge formation and is more prominent than bedding.

Modes of the Partridge formation estimated from thin sections are shown in Table 1, columns 15 to 18. The essential minerals are quartz, oligoclase, biotite, and muscovite. These rocks average from 0.05 to 0.80 millimeter in diameter for the middle-grade zone, and the porphyroblasts of garnet and biotite range from 0.2 to 1.5 milimeters. In the high-grade zone the groundmass is somewhat coarser, and the sillimanite porphyroblasts reach 6.0 millimeters in length. The biotite of the high-grade zone is iron-rich. The optical properties of muscovite are similar to those of pure muscovite analyzed by Barth (1936, p. 781). The garnets from both the middle- and high-grade zones have properties similar to those of almandite described elsewhere in New England. Accessory minerals are magnetite, clinozoisite, sphene, zircon, tourmaline, and leucoxene.

Augen containing relics of sillimanite altered to muscovite are surrounded by crushed zones of quartz which are wrapped with coarse micas. The prevalence of sutured grain boundaries probably shows that there has been complete recrystallization of the rock after granulation.

The Partridge formation ranges in thickness from 500± to 2000± feet. The thickness is variable because of the pronounced unconformity that separates the

Partridge formation from the overlying Clough and Littleton formations. The abnormal breadth of outcrop in the southern part of the quadrangle is due to repetition of the strata by folding.

SILURIAN STRATA

CLOUGH FORMATION

The only Silurian strata recognized in the Bellows Falls quadrangle are those of the Clough formation. This distinctive unit is a key horizon useful in solving the structure.

In general, the Clough formation occupies discontinuous bands concentric about bodies of the Oliverian magma series. One area is 3 miles west of the northeast corner of the quadrangle, in the valley of Pierce Brook in Acworth township. A second narrow discontinuous belt extends in a northerly direction from 1 mile south of Alstead Center, crosses Cold River, then sweeps in a great arc to Beryl Mountain, thence south to Prentice Hill. A third belt, likewise discontinuous, extends southwest from Shaws Corner, in the northern part of Surry township. Isolated shallow synclinal outliers of the Clough formation cap the tops of Surry Mtn. and Webster Hill in Gilsum township, and an isolated anticline of the quartzite appears on the slopes of Watkins Hill in Walpole township.

There is little difference in the lithology of the formation in the middle- and high-grade zones. The Clough formation is predominantly pure, white, coarse- to medium-grained quartzite and quartz conglomerate with small amounts of mica schist. In only two localities were garnet porphyroblasts noticed. The ellipsoidal pebbles are 1 to 12 inches long, with a ratio of short to long axes of 1 to 6. An estimated mode of the Clough formation appears in Table 2, column 1.

The maximum measureable thickness of the Clough formation is 300± feet on the east side of Pierce Brook in Acworth township, but it may be thicker on Joslin Hill in Surry township, where folding accounts for an excessive width of the outcrop, but the thickness here is indeterminable. The discontinuous nature of the Clough formation is due in part to the original variation in thickness because of unequal sedimentation, in part to tectonic reasons, and in part to the failure to crop out. Where it does not crop out the horizon of the formation is shown by a dash-dot line on the geological map (Pl. 1) for purposes of interpretation.

DEVONIAN STRATA

LITTLETON FORMATION

General statement.—The Devonian strata of western New Hampshire belong to the Littleton formation, which is the most extensive lithologic unit in the Bellows Falls quadrangle. In a belt 1 to 3 miles wide along the eastern margin of the quadrangle the metamorphism is high-grade, elsewhere it is middle-grade. Within the Bellows Falls quadrangle the schists and volcanics of the formation contain two quartzitic members with some associated lime-silicate beds.

Schists.—Originally much of the Littleton formation was arenaceous shale, but now consists for the greater part of light- to dark-gray, fine- to medium-grained mica

schist, mica-quartz schist, and quartz-mica schist. Porphyroblasts of biotite, staurolite, and garnet occur in all three varieties of schist. Their high-grade equivalents are coarse muscovite schist, muscovite-biotite-quartz schist, and quartz-mica schist, all of which contain porphyroblasts of garnet and sillimanite. These schists show a remarkable development of bedding-plane schistosity.

The composition of the middle-grade schists of the Littleton formation is shown by the estimated modes in Table 2, columns 9 to 14. The groundmass ranges from 0.02 to 0.80 millimeter in diameter, and the size of the biotite and garnet porphyroblasts is 0.5 to 2.0 millimeters. Evidence of rotation in porphyroblasts is common. Staurolite crystals which attain a length of 6.0 millimeters occur as pseudomorphs of sericite and as irregular sericitized knots. The feldspar is oligoclase-andesine. The chlorite is optically positive ripidolite. Accessory minerals are zircon, apatite, magnetite, graphite, leucoxene, and epidote.

Modes of the rocks from the high-grade zone appear in Table 2, columns 18 to 23. The schists in the high-grade zone are much coarser than those in the middle-grade zone, the groundmass averaging 0.1 to 3.0 millimeters and the porphyroblasts 0.5 to 8.0 millimeters. The large crystals of sillimanite alter to muscovite or to swirls of fine sericite.

The biotite from both the middle- and high-grade zones is intermediate in composition. The properties of muscovite are comparable with those of pure muscovite. The garnets from schists of the Littleton formation of both the middle- and high-grade zones are probably almandite-spessartite.

Quartzites.—The Littleton formation contains two thin, discontinuous quartzite members. Where these quartzites do not crop out the deduced horizons have been indicated by a dash-dot line to facilitate interpretation (Pl. 1).

These rocks are relatively pure, white to buff-gray, fine- to medium-grained quartzites and quartz conglomerate with varying amounts of micaceous material in the matrix. The pebbles are ellipsoidal and range from 2 inches to several feet in length. The average pebble has axial ratios of 1 to 2 to 4, but the extreme may reach 1 to 2 to 12. The pebbles are probably all vein quartz and chert, although some slate and schist are present. In one locality an unidentifiable metamorphosed granite boulder was found. Some of the quartzites carry garnet porphyroblasts. In the high-grade zone the quartzites are coarsely recrystallized, but the mineral composition remains the same.

Table 2, columns 2 to 4, shows the estimated modal composition. The essential minerals are quartz, albite-oligoclase, biotite, and muscovite. The accessory minerals are magnetite, limonite, calcite, zircon, epidote, tourmaline, garnet, and rutile. The quartzites of the Littleton formation have granoblastic textures averaging 0.02 to 0.30 millimeter in grain size. The porphyroblasts of biotite and garnet are from 0.5 to 0.7 millimeter in diameter. The biotite and muscovite are similar in composition to those occurring in the schists already discussed.

Lime-silicate granulites and biotite-quartz schists.—Associated with the two quartzite members are buff to grayish-green, medium-grained lime-silicate granulites and brown, medium-grained biotite-quartz schists. The original rocks were respectively impure limestones and shales. The principal minerals, as indicated by representa-

tive modes given in Table 2, columns 5 to 8, are quartz, biotite, and amphibole; minor minerals are calcite, zoisite, pyroxene, and sphene.

The lime-silicate rocks are very distinctive, partly because the weathered faces are covered with solution pits ⅛ to ½ inch deep. Bedding is more prominent than schistosity, but many outcrops show a pronounced fracture cleavage. The beds differ in color because of variations in the relative amounts of amphibole and biotite, beds rich in the former tending to light-green shades, beds rich in the latter tending to dark-brown shades. Porphyroblasts, which are rare and consist principally of biotite, less commonly of amphibole and garnet, range in size from 0.1 to 2.0 millimeters. Microscopic study shows that these lime-silicate rocks in general have granoblastic textures with grains averaging 0.1 to 0.7 millimeter in size. Lenses, which are 2 to 8 inches long and contain coarse amphibole and diopside, probably represent deformed concretions.

The optical data indicate that the amphibole is magnesium-rich and is similar to that found in the Fitch formation by Billings (1937, p. 486) in the Moosilauke area. The optical properties of the biotite also indicate a predominance of magnesia. The plagioclase ranges from andesine to labradorite. No potash feldspar was found in these rocks.

Volcanics.—Several lenses of volcanics are found in the Littleton formation. Near the top of the formation at Hemlock School, Charlestown township, thick-bedded felsitic and amphibolitic rocks are present. Amphibolites also occur near the top of the formation on Balls Hill, Langdon township; on Cheney Hill, Walpole township; and lower in the formation on Watkins Hill, Walpole township. These lenses are dominantly medium- to coarse-grained, banded amphibolites, although some banded porphyritic felsitic members are present.

The composition of both types of volcanics are listed in Table 2, columns 15 to 17. The amphibole schist contains amphibole, andesine, some quartz, magnetite, sphene, apatite, zircon, and leucoxene. The felsitic volcanics of this formation are granoblastic and have porphyroblasts of garnet from 2.0 to 3.0 millimeters in diameter. Phenocrysts of quartz and andesine from 0.5 to 1.5 millimeters in diameter are also present. The groundmass averages from 0.01 to 0.30 millimeter in grain size and consists dominantly of quartz and feldspar with only a small amount of dark minerals.

Thickness.—The Littleton formation is approximately 6000 feet thick. This figure is comparable with the estimates made by Billings (1937) and Chapman (1939). The two quartzite members each have a maximum thickness of 100 feet, but they probably average less than 20 feet. The lime-silicate granulite member reaches a maximum thickness of 2000 feet but is absent in much of the quadrangle. The volcanics likewise occur as lenses but have a maximum thickness of approximately 100 feet.

CORRELATION OF STRATA

No fossils have been discovered as yet in the Bellows Falls quadrangle. Hence the dating of the formations is based upon correlations with other areas.

The calcareous strata in the northwest corner of the quadrangle are correlated

TABLE 2.—*Estimated modes of the Clough and Littleton formations*

	Clough Formation	Littleton Formation																							
		Quartzites			Lime-Silicate Granulites and Associated Schists				Middle-Grade Schists									High-Grade Rocks						Injection Gneiss		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Porphyroblasts:																										
Chlorite													2													
Amphibole					tr																					
Biotite				15	5				7	7	5	3														
Garnet		2			tr	2			tr	3	1	1	5		5	3		3		1				3	4	3
Staurolite									tr		tr	11														
Muscovite																		2			15					
Sillimanite											tr							7								
Phenocrysts:																										
Quartz															8											
Plagioclase															5			tr								5
Groundmass:																										
Quartz	99	85	97	70		46	85	65			53		45	47		45	4	38		30	15	40		33	20	25
Potash feldspar		3			41				52	75	16	37	9	35	80	45	35	7	80	10	20	25	48	15	10	20
Plagioclase				tr		9	1	1						12				5	10	10	10	20		15	15	25
Muscovite	1		tr	3		5	3		28	10	21	31	24	2		2		13	tr	12	20	4	1	9	25	10
Biotite				8	20	31		15	4	3	4	17	12	4	2	2		25	10	35		10	1	25	15	7
Chlorite		10		3	tr	4	3		8	2	tr	tr	3		tr	2		tr		tr	20				10	4
Pyrite								2						tr							tr			tr		tr
Magnetite		tr		tr	tr		3		1		tr	tr	tr				tr	tr						tr	1	1
Carbon												tr														
Limonite			tr				tr							tr		1		tr						tr		
Leucoxene									tr			tr					tr									
Amphibole					28			15									60									
Sphene					1												tr									
Calcite			tr		2			1																		
Zircon			tr		tr	tr	tr	tr	tr	tr	tr	tr	tr				tr	tr	tr	tr	tr			tr	tr	tr
Apatite		tr			tr	tr		tr		tr			tr					tr		tr	tr	tr		tr		
Zoisite*			3	1	1		5	1																		
Tourmaline			tr		tr	tr			tr	tr	tr	tr	tr		tr			tr		2						
Pyroxene					2																					
Garnet			tr			3																1	50			
Texture†	G	G	G	G	S	S	G	G	S	S	S	S	S	G	G	G	S	G-S	G	S	fi	S	G	S-G	S-G	S-G

Pyroxene			tr		2	1									1								1	50				
Garnet																													
Texture†	G	G	G	G	S	S	G	G	S	S	S	S	S	G	G	G	S	G-S	G	S	S	S	G	S-G	S-G	S-G			

Size of porphyroblasts in mm. .		0.70		0.50	0.60–2.00	0.10–0.50			0.50–1.50	0.70	0.50–1.80	0.50–6.00	0.40–1.40	2.00	2.00–0.50	3.00	2.00	0.50–8.00			6.00	0.10		0.20–0.70	4.00				
Size of phenocrysts in mm.....															1.50			1.00								3.00			
Size of groundmass in mm.....	0.10–1.00	0.10	0.02–0.07	0.10–0.30	0.10–0.50	0.03–0.10	0.10–0.20	0.10–0.70	0.05–0.70	0.05–0.20	0.05–0.80	0.02–1.00	0.05–0.10	0.10–0.50	0.01–0.30	0.10–0.20	0.10–1.50	0.20–0.90	0.30–0.70	0.50–3.00	1.50	0.10–0.50	0.05–0.10	0.20–3.00	0.70–1.00	0.50–1.50				

* Includes epidote and allanite.

† S = schistose, G = granoblastic.

1. Quartzite.
2. Thin-banded garnet quartzite.
3. Thin-banded quartzite.
4. Micaceous quartzite.
5. Biotite-amphibole granulite (average of 2 thin sections).
6. Brown biotite schist (average of 2 thin sections).
7. Brecciated siliceous granulite (calcite leached).
8. Biotite-amphibole-quartz granulite.
9. Banded mica schist.
10. Garnet-mica-quartz schist.
11. Mica-quartz schist (average of 3 thin sections).
12. Staurolite-mica schist (average of 6 thin sections).
13. Garnet-mica schist (average of 4 thin sections).
14. Quartz-mica schist.
15. Garnetiferous felsite.
16. Thin-banded garnet felsite.
17. Amphibolite.
18. Sillimanite-biotite schist (average of 5 thin sections).
19. Thick-bedded biotite quartzite.
20. Biotite schist.
21. Muscovite schist.
22. Quartz-mica schist.
23. Garnet granulite.
24. Biotite-feldspar gneiss (average of 2 thin sections).
25. Garnet-mica gneiss.
26. Garnet-mica-feldspar gneiss.

with the Waits River formation of central Vermont (Currier and Jahns, 1941) because of lithologic similarity. Moreover, these calcareous rocks may be traced continuously from the Bellows Falls quadrangle to central Vermont (Hitchcock, 1878; White and Eric, 1944). In the past the Waits River formation has been assigned to the Ordovician because of supposed graptolites reported by Richardson (1919). Modern investigators agree, however, that these "graptolites" are merely a linear streaking of micas (Foyles, 1931). But Currier and Jahns (1941) have shown that the base of the Waits River formation is more than 2000 feet stratigraphically above a thin crinoidal limestone, and, because crinoids did not appear until the latest Cambrian, the Waits River formation is Ordovician or younger. Moreover, Josiah Bridge and P. E. Raymond say that the size and relative abundance of the crinoids suggest that the beds containing them cannot be older than middle Ordovician (Currier and Jahns, 1941, p. 1500–1501). It is apparent, therefore, that the Waits River formation is middle Ordovician or younger.

The Orfordville formation, which overlies the Waits River formation, may be traced continuously from the Bellows Falls quadrangle to the type locality in the Mt. Cube quadrangle, 45 miles to the northeast (Hadley, 1942). The Orfordville formation of the type locality is overlain by the Albee, Ammonoosuc, Partridge, Clough, Fitch, and Littleton formations, in that order. The Fitch contains middle Silurian fossils (Billings and Cleaves, 1934), and the Clough, because it is closely associated with the Fitch, is considered to be middle or lower Silurian. Moreover, the Silurian strata rest unconformably upon the older formations.

From this discussion, it is obvious that the Waits River, Orfordville, Albee, Ammonoosuc, and Partridge formations cannot be older than middle Ordovician but are pre-Silurian. The upper three formations are assigned to the upper (?) Ordovician, the lower two to the middle (?) Ordovician. Just where to place the boundary between middle and upper Ordovician is obviously problematical. The assignments are in agreement with Billings (1934), who, however, based his conclusions in part upon the now-discredited "graptolites" of the Waits River formation.

The Littleton formation of the Bellows Falls quadrangle may be traced continuously northwestward 60 miles to the Littleton-Moosilauke area, where lower Devonian fossils occur (Billings and Cleaves, 1934; 1935).

MISSING FORMATIONS

Portions of the stratigraphic column (Fig. 3) are missing in the Bellows Falls area, some because of tectonic reasons, some are absent because they were not deposited, and some are cut out by intrusions.

In western New Hampshire an unbroken upper Ordovician (?) stratigraphic sequence has been demonstrated (Hadley, 1942), but in the northwestern part of the Bellows Falls area a considerable amount of this section has been cut out by the Northey Hill fault. Missing because of this thrust are the upper 1000± feet of the Ordfordville formation, all of the Albee formation, consisting of 4000± feet of thin quartzites and mica schists, and the lower 2000± feet of the Ammonoosuc volcanics.

The calcareous Fitch formation, which carries Niagaran fossils in the Littleton region, pinches out southward and is not found in the Bellows Falls quadrangle.

AGE	FORMATION	SYMBOL	COLUMNAR SECTION	LITHOLOGY	THICKNESS IN FEET	LOCALITY	INTRUSIVE
QUATERNARY	DRIFT AND ALLUVIUM	d		Till, outwash, and alluvium	0-200 ±		
INTRUSIVES ARE YOUNGER THAN LOWER DEVONIAN							WHITE MTN. MAGMA SERIES (wm)
LOWER DEVONIAN	LITTLETON FORMATION	Dl Dli Dlv Dlq Dll Dlq Dl		Mica schist, mica-quartz schist, and quartz-mica schist; each may have porphyroblasts of biotite, garnet, staurolite, or sillimanite (Dl); injections of Bethlehem gneiss in Littleton formation (Dli); quartzite and quartz conglomerate (Dlq); lime-silicate granulite and schist (Dll), amphibolite and felsite volcanics (Dlv).	0-200 ± 0-2500 ± 0-500 ±	SECTION EAST OF NORTHEY HILL THRUST 6000 ±	NEW HAMPSHIRE MAGMA SERIES (nh)
				Missing or change of facies makes it indistinguishable from Littleton formation			
	MIDDLE	Sf		Quartz conglomerate, quartzite and quartz-mica schist	0-300 ±		OLIVERIAN MAGMA SERIES (ol)
SILURIAN	MIDDLE OR LOWER	Sc		Mica schist, mica-quartz schist, quartz-mica schist, and quartzite, each may have porphyroblasts of biotite, garnet, sillimanite	500-2000 ±		
	UNCONFORMITY						
PRE-SILURIAN, PROBABLY ORDOVICIAN	PARTRIDGE FM.	Op		Amphibolite, some biotite gneiss	500-2000 ±		
UPPER (?)	AMMONOOSUC VOLCANICS	Oam		Lower part of Ammonoosuc volcanics, all of Albee formation, and upper part of Orfordville formation, are present elsewhere but are missing in this quadrangle due to the Northey Hill thrust.	2000 (?)	SECTION CUT OUT BY NORTHEY HILL THRUST	
	ALBEE FORMATION	Oal			4000 (?)		
MIDDLE (?)	ORFORDVILLE FORMATION	Oo Ooh Oov			1000 (?)		
				Slate, graphitic sericite schist, graphitic mica schist, mica schist, and paper-thin quartzite; each may have porphyroblasts of biotite, garnet, or staurolite (Oo); quartzite and quartz conglomerate (Ooh); chlorite schist, amphibolite, and some biotite gneiss (Oov)	0-160 ± 0-500 ±	SECTION WEST OF NORTHEY HILL THRUST 4000 ±	
	WAITS RIVER FORMATION	Ow		Mica-quartz schist, calcareous mica-quartz schist; each may have porphyroblasts of biotite and garnet. Also impure marble.	2000 (?)		

FIGURE 3.—*Columnar section for the Bellows Falls quadrangle*

This change in facies was noted by Hadley (1942) and Chapman (1939), both of whom described the thickening of the Clough formation as being coincident with the thinning of the Fitch formation.

Conversely the Partridge formation of the Littleton quadrangle, which pinches out in the intervening quadrangles, reappears in the Bellows Falls quadrangle to consitute an important part of the stratigraphic column. Minor changes in composition and texture have also been noted in the Ammonoosuc volcanics. The formation was dominantly soda-rhyolite to the north, but to the south the amphibolitic facies have been more prominent.

PLUTONIC, SILL, AND DIKE ROCKS

GENERAL STATEMENT

Plutonic rocks, in many instances foliated, make up approximately one-third of the rocks of the Bellows Falls quadrangle. They consist of fine- to medium-grained granites and quartz monzonites belonging to the Oliverian and New Hampshire magma series. The late Ordovician (?) Highlandcroft magma series is not present. The Oliverian magma series occupies the cores of a series of domes. Representatives of the New Hampshire magma series occur in three localities: an eastern pluton, a sill-like body around Fall Mtn., and smaller isolated intrusive masses. As a rule the plutonic rocks occupy topographic lowlands surrounded by highlands of resistant country rock.

Post-metamorphism dikes and sills of camptonite, one of which constitutes a mappable body, belong to the White Mtn. magma series. Minor igneous injections include pre- and post-metamorphism sills and dikes. Pegmatites are abundant especially in the eastern third of the mapped area.

OLIVERIAN MAGMA SERIES

Gneiss of the Alstead dome.—The gneiss of the Alstead dome extends from Smith Hill, in the southeast corner of the quadrangle, for 12 miles north to Osgood Ledge. The rock is characteristically salmon-pink, fine- to medium-grained biotite gneiss. Locally it exhibits a subporphyritic texture with milky or smoky quartz eyes set in a groundmass of granular feldspar, quartz, and mica. Aggregates composed of small particles of biotite give the appearance of large single flakes. Feldspar phenocrysts are scarce.

The foliation caused by biotite is well marked near the border of the dome but diminishes toward the center. Locally the composition of the overlying Ammonoosuc volcanics very nearly approaches that of the gneisses of the Oliverian magma series, so that the contact is difficult to locate. Inclusions of volcanic material are very abundant near the margins of the main body of the gneiss. This contaminated phase is difficult to distinguish from Ammonoosuc volcanics that are thoroughly injected by sills.

Microscopic examination shows hypidiomorphic textures, although granoblastic and blastoporphyritic textures are common. Some specimens have a marked development of mortar and augen structures. Post-solidification deformation is

evidenced by bent and mashed muscovite and epidote. The granulation of the Oliverian magma series was probably contemporaneous with the formation of the regional schistosity. At one place in the field the schistosity transgresses both the bedding of the metamorphosed sediments and the dikelets of the Oliverian magma series.

Modes estimated from thin sections appear in Table 3, columns 1 and 2. The essential minerals are quartz, potash feldspar, oligoclase-andesine, and biotite. Accessory epidote, apatite, zircon, garnet, and magnetite may also be present. Myrmekitic intergrowths which may comprise as much as 3 per cent of the rock are especially abundant in crushed zones. Strain shadows are common in quartz and biotite. The average biotite is red brown and is intermediate in composition. The optical properties of the muscovite indicate that it is a low-iron and low-magnesium variety. Epidote of a low-iron variety is conspicuously associated with sheaves of biotite and along crushed zones, as if related to late channels of ingress. The rock type ranges from granite to quartz monzonite, but the average is a quartz monzonite.

Gneiss of the Surry dome.—This body of gneiss occupies the lowland of the Ashuelot River in Surry township. The rock is similar to the gneiss of the Alstead dome. Modes of thin sections from this body appear in Table 3, columns 3 and 4.

Correlation.—The Oliverian magma series was considered by Billings (1937) to be younger than the lower Devonian, because he believed it had domed the Littleton formation along with the Fitch, Clough, Partridge, and Ammonoosuc formations. Sills and dikes of the gneiss cut the Ammonoosuc volcanics, and Chapman (1939) reports that it intrudes the Clough formation. On the southeast side of the Alstead dome the gneiss intrudes schists, some of which belong to the Partridge formation and some of which may belong to the Littleton formation. The age of the Oliverian magma series relative to the regional deformation will be discussed later.

NEW HAMPSHIRE MAGMA SERIES

Bethlehem gneiss.—The Bethlehem gneiss of the New Hampshire magma series comprises the Mt. Clough and Bellows Falls plutons. The Mt. Clough pluton crops out in the northeast part of the quadrangle where it is especially well exposed on Grout Hill in Acworth township. Gneiss of the Bellows Falls pluton is well exposed in the gorge of the Cold River east of the village of Alstead and on the knolls along Jabes Meadow Brook, Charlestown township. The Bethlehem gneiss also appears as small intrusive lenses in the high-grade schists in the eastern part of the quadrangle and in the schists of Fall Mountain.

The Bethlehem gneiss is a light- to dark-gray, fine- to medium-grained granular rock. Only locally is it coarse-grained, and this phase is accompanied by augenlike phenocrysts of quartz and feldspar up to 3.0 millimeters long. The biotite flakes are large, averaging 3.0 millimeters, though they may be mashed and stretched parallel to the lineation. Zones of pseudo-tachylite are developed locally. The Bethlehem greiss is characterized by an especially good foliation due to a large percentage of micas. Near contacts this is particularly noticeable because of contamination by the schistose host rocks. The composition of the Bethlehem gneiss is given in Table 3, columns 5 to 10. The essential minerals are quartz, potash feldspar, sodic andesine, biotite, and muscovite. The rock is characteristically rich in biotite.

TABLE 3.—*Modes of plutonic, sill, and dike rocks*

	OLIVERIAN MAGMA SERIES				NEW HAMPSHIRE MAGMA SERIES								WHITE MOUNTAIN MAGMA SERIES
	1	2	3	4	5	6	7	8	9	10	11	12	13
Quartz	39	36	36	44	59	20	23	25	25	28	40	14	7
Orthoclase	37	30	44	26	16	20	23	28	15	29	33		10
Plagioclase	13	26	13	22	8	40	25	29	36	35	17	22	38
Biotite	6	7	6	4	2	16	27	11	20	8	6		
Muscovite	1	tr	tr	tr	15	2	2	tr	1	tr	4	tr	
Zoisite*	3	1	1	4			tr	tr			tr	tr	
Sphene		tr							tr		tr	tr	tr
Garnet	tr	tr	tr			2	tr	tr	tr				
Apatite	tr	tr	tr	tr	tr		tr	tr	tr	tr	tr	tr	
Magnetite	1		tr				tr		tr		tr	1	
Rutile	tr		tr										
Pyrite	tr		tr					tr			tr		
Pyroxene			tr										
Amphibole								7	3			56	27
Calcite											tr	tr	3
Tourmaline									tr				
Zircon	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr		
Chlorite	tr		tr		tr		tr	tr	tr		tr	7	15
Per cent of anorthite in plagioclase	27	29	30	31	24	33	35	33	38	35	24	46	50
Size of phenocrysts in mm.	1.0–2.5	1.5–3.0	1.0–3.0	1.0–2.0			1.0–3.0	2.0–3.0	2.0–2.5	1.8–3.0			1.0–2.0
Size of groundmass in mm.	0.3–0.8	0.4–0.8	0.1–0.6	0.3–0.6	0.5–1.0	0.6–1.2	0.2–0.7	0.1–0.7	0.2–0.7	0.4–1.0	1.0–2.2	0.1–2.0	0.1–0.5

* Including epidote and allanite.

1. Granite gneiss, Oliverian magma series, Alstead dome (average of 4 thin sections).
2. Quartz monzonite gneiss, Oliverian magma series, Alstead dome (average of 4 thin sections).
3. Granite gneiss, Oliverian magma series, Surry dome (average of 3 thin sections).
4. Quartz monzonite gneiss, Oliverian magma series, Surry dome.
5. Contaminated Bethlehem gneiss, New Hampshire magma series, Mt. Clough pluton.
6. Bethlehem gneiss, granodiorite facies, New Hampshire magma series, Mt. Clough pluton.
7. Bethlehem gneiss, quartz monzonite facies, New Hampshire magma series, Mt. Clough pluton (average of 4 thin sections).
8. Bethlehem gneiss, quartz monzonite facies, New Hampshire magma series, lower part of Bellows Falls pluton (average of 3 thin sections).
9. Bethlehem gneiss, granodiorite facies, New Hampshire magma series, lower part of Bellows Falls pluton (average of 2 thin sections).
10. Bethlehem gneiss, quartz monzonite facies, New Hampshire magma series, upper part of Bellows Falls pluton (average of 3 thin sections).
11. Granites, New Hampshire magma series, isolated bodies (average of 9 thin sections).
12. Pre-metamorphism amphibolitic dikes and sills (average of 6 thin sections).
13. Post-metamorphism camptonite dikes, White Mtn. magma series (average of 2 thin sections).

The heavy accessory minerals concentrated by bromoform and magnets from six specimens of the Bethlehem gneiss comprise 16.7 per cent of the bulk samples. Of this amount the percentage distribution by weight is 97.64 per cent biotite, 0.81 per cent fluorapatite, 0.51 per cent magnetite, 0.50 per cent unidentified opaque, 0.16 per cent chlorite, 0.10 per cent zircon, plus traces of epidote, green, blue, and brown tourmaline, hornblende, monazite, and garnet. No diagnostic mineral ratios were discovered.

Under the microscope the Bethlehem gneiss has a granoblastic texture, but flaser, augen, and mortar structures are common. Under crossed nicols bent twin lamellae and strain shadows in feldspar and quartz are commonly seen. Quartz and feldspar augen and crushed lenses are surrounded by a finer-grained groundmass averaging 0.5 millimeter. Myrmekitic intergrowths are found to a limited degree.

Injection gneiss.—In the high-grade zone, in the eastern part of the quadrangle, injection gneisses are developed locally. Typical exposures may be seen on Smith Hill 2 miles southeast of Lake Warren in Alstead township. Some injection gneiss is also developed in the schists on Fall Mountain. This phase is excellently exposed in the gorge of the Connecticut River across from Bellows Falls.

The injection gneiss consists of mica schist and mica-quartz schist intimately injected by lenses of coarse-grained igneous rock from an inch to many feet long. The average lens is 12 inches long and 2 inches thick. The injection gneiss is light gray to dark gray because of the content of micas, and in addition it contains visible amounts of garnet and sillimanite. Modes of the injection gneiss are given in Table 2, columns 24 to 26. In addition to quartz, microcline, oligoclase, biotite, and muscovite, smaller amounts of zircon, magnetite, chlorite, and pyrite are also present.

The injection gneiss is schistose to granulose in texture. Augen consisting of granular aggregates or of crushed phenocrysts commonly display mosaic and mortar structures. Porphyroblasts of garnet and sillimanite are from 0.2 to 7.0 millimeters in diameter; phenocrysts of feldspar are from 1.0 to 3.0 millimeters in diameter. Under the microscope the abundant muscovite and accessory garnet and sillimanite are conspicuous. The sillimanite is partially retrograded to muscovite, but relic crystals may be 7.0 millimeters long.

Although the typical injection gneiss has quartz and feldspar in excess of the normal content of igneous rocks, the larger lenses of injected material maintain the mineralogical identity of the parent pluton. It is significant that in the parent pluton of the Bethlehem gneiss the plagioclase is andesine (A_{30-38}), whereas in the injection gneiss it is oligoclase (An_{11-26}). This shows an effective addition of soda and potash to the feldspar accompanying the assimilation of some of the schists.

Granites.—The biotite-muscovite granites of the Bellows Falls region occur as stocks, sills, and dikes in the western third of the quadrangle. One irregular stock covering three quarters of a square mile was mapped at Westmoreland Depot. Wherever the contact was observed it was vertical; in one place it is crosscutting, and in another it is concordant.

A sill 2 miles long and averaging 300 feet wide, a mile east of Parker Hill in the northwest corner of the quadrangle, is concordant and lenses out to the north and

south. A similar body is located in Westminster township. Its contacts with the schists of the Littleton formation appear to be concordant on the east and north sides, but on the west it is partly crosscutting and partly faulted. The southern border is unexposed.

In hand specimen these rocks are light-gray to flesh-colored, medium-grained biotite-muscovite granites similar to the Bickford and Concord granites in the quadrangles to the north. Some phases are foliated, but most are massive. The essential minerals are quartz, potash feldspar, oligoclase-andesine, muscovite, and biotite. The modes, which are summarized in Table 3, column 11, indicate that these rocks are close to the boundary between granite and quartz monzonite. The minerals in the groundmass are 0.1 to 0.8 millimeter in diameter. Some phases of the granite are porphyritic, having phenocrysts of microcline and oligoclase from 1.2 to 2.2 millimeters in diameter.

Correlation.—Because the Bethlehem gneiss intrudes the schists of the Littleton formation it is known that it is younger than lower Devonian. This dating is corroborated by a lead-uranium ratio from related pegmatitic rocks (Shaub, 1938, p. 339), which suggests a middle or late Devonian age. The intrusion of the Bethlehem gneiss and its relationship to the structure and metamorphism will be discussed later.

The precise dating of the granites in this area must be indefinite because no crosscutting relationships exist between the various intrusive igneous bodies. Their lack of strong foliation and the fact that they contain random and oriented inclusions showing a folded schistosity strongly suggest a post-metamorphism age. By analogy to similar occurrences elsewhere in New Hampshire these granites are late members of the New Hampshire magma series.

SILLS AND DIKES

Pre-metamorphism.—Metamorphosed sills and dikes were observed in the Partridge and Littleton formations. These pre-metamorphism intrusives are greenish-gray to black, medium- to coarse-grained schistose amphibolites. Thin-section study shows that thery are chiefly quartz, andesine-labradorite, and chloritized amphibole. Use of the gypsum plate under crossed nicols indicates a high degree of crystallographic orientation. Few pre-metamorphism felsic dikes are present. Modes are summarized in Table 3, column 12.

Post-metamorphism.—Camptonite dikes and sills are aphanitic dark-gray rocks that weather to buff-gray. In places the calcite filling the amygdules has been leached to give a vesicular structure. As indicated in Table 3, column 13, the essential minerals are andesine-labradorite and barkevikite; some quartz and orthoclase are present.

One body on Prospect Hill, in the township of Charlestown, covers approximately a quarter of a square mile and is large enough to appear on the geological map. The body, which is a dike that dips gently south, is characterized by excellent columnar jointing in many exposures. The attitude of these columns shows the dike followed an irregular surface during emplacement.

Numerous small porphyritic and nonporphyritic mafic dikes cut all of the other rocks in the area. The thicker porphyritic dikes showed flow structure by the

arrangement of the phenocrysts. Although the camptonite dikes belong to the White Mountain magma series, some of the other mafic dikes may be Triassic.

Pegmatites.[2]—In the eastern half of the Bellows Falls quadrangle pegmatite dikes and sills are common. Many of the prominences are held up by this resistant rock. The smaller pegmatites are concordant, but many of the major ones are crosscutting. The pegmatites are spatially related to the Oliverian magma series and to the Bethlehem gneiss. Reconnaissance study gave the impression that the pegmatites which are associated with the Oliverian magma series are of simpler mineralogy, whereas those farther east near the Bethlehem gneiss have tourmalinized borders, more mica, and a greater variety of minerals.

Within the Bethlehem gneiss only minor pegmatitic segregations are present in joints along which movement took place before complete solidification of the magma. This shear caused a filter-press action separating pegmatitic juices from the mesh of dark minerals. Concentrations in thin lenses a few inches long consisting of quartz and feldspar are present on Smith Ledges southeast of Lake Warren. These are similar to those described by Chapman (1939, p. 147).

Chapmsn showed that the pegmatites of the Mascoma area belong to the Bethlehem gneiss and are localized at its upper contact. In the Bellows Falls quadrangle the largest pegmatites are stratigraphically above the Oliverian magma series, but are stratigraphically a few thousand feet below the intrusive horizon of the Bethlehem gneiss. Numerous smaller pegmatites are closely associated with the Bethlehem gneiss and the injection gneiss.

The pegmatites are post-metamorphism, because they crosscut schistose beds and contain inclusions which display folded schistosity. Only one pegmatite dike, on the hill west of Caldwell Pond, in Alstead township, is older than the metamorphism.

STRUCTURE

GENERAL STATEMENT

The Bellows Falls quadrangle, although containing the same structural units as mapped farther to the northeast, presents an unexpected problem because beds with low dips crop out in a region of moderate relief. The pattern of gently undulating key beds in rolling terrain partially covered by glacial drift is difficult to ascertain.

The first-order folds have a wave length of a few miles and an amplitude of several thousand feet. The trends of major folds, faults, and plutons reflect the northeast-southwest regional grain. The larger structural units from east to west are: (1) the Mt. Clough pluton; (2) the Oliverian domes along the Bronson Hill anticline; (3) the Walpole syncline intruded by the Bellows Falls pluton; (4) the Northey Hill thrust, and (5) the Charlestown syncline. Numerous local high-angle normal (?) faults were discovered in detailed mapping, but only the more important appear on the geological map. For purposes of description the major structural features will be considered in order from east to west.

[2] *Editorial note:* On his original map Mr. Kruger indicated each pegmatite outcrop merely by a cross, because his investigation was not economic in scope. In the summer of 1944 Mr. G. W. Stewart, working for the U. S. Geological Survey, re-examined many of these pegmatites and determined their attitude. The data obtained by Mr. Stewart have been incorporated on Plate 1, the attitude of each pegmatite being indicated by an appropriate symbol. Those pegmatites recorded by Mr. Kruger but not restudied by Mr. Stewart are indicated by a red cross on Plate 1.

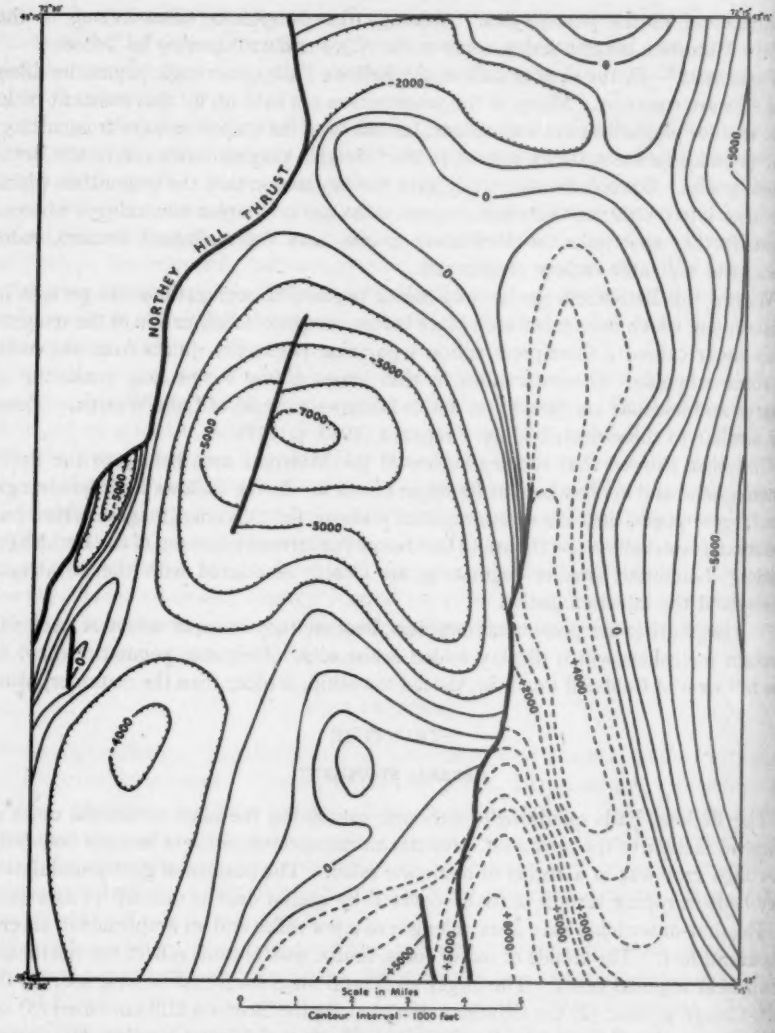

FIGURE 4.—*Structure contour map of the Bellows Falls quadrangle*

Contours drawn on Clough formation. Datum is sea level. Dashed contours above surface. Faults in heavy lines

In addition to the geological map and structure sections (Pl. 1), a structure contour map (Fig. 4) is presented as an interpretation of the structure. The structure contours are drawn on top of the Clough formation. A tectonic map (Pl. 2), which gives the pattern and distribution as well as the attitudes of the folds, bedding, and foliation, is also presented.

MT. CLOUGH PLUTON

The Mt. Clough pluton has been mapped for over 100 miles along the regional strike in western New Hampshire. This body occupies a portion of the northeast corner of the Bellows Falls quadrangle and a part of the area just east of the boundary of the quadrangle.

The schistosity in the Littleton formation west of the Mt. Clough pluton dips east beneath the Bethlehem gneiss at gentle angles. Although the actual contact was nowhere seen the intrusive is believed to be concordant. The strike of the bedding and schistosity of the Littleton formation and the strike of the foliation of the Bethlehem gneiss are parallel to the contact. To the north, where relief is greater, it is possible to show that the foliation of the gneiss is parallel to the contact in three dimensions (Billings, 1937, p. 536; Pl. 12). In the schists between the Mt. Clough pluton and the Oliverian magma series, the minor fold axes and the linear mineral streaking tend to plunge directly down the dip of the schistosity.

The foliation of the Bethlehem gneiss is well developed at the margin of the pluton, dips approximately 30°E., and continues to be well developed toward the center of the body. The mineral lineation and the long axis of oriented inclusions plunge nearly down the dip of the foliation. The data indicate that the Bethlehem gneiss in the northeast corner of the quadrangle is the west side of a concordant pluton dipping 30°E. The lineation shows that the pluton was intruded upwards to the northwest into metamorphosed sediments.

BRONSON HILL ANTICLINE

General statement.—The Bronson Hill anticline has been traced for 140 miles from the Mt. Washington quadrangle, New Hampshire (Billings, 1941), into central Massachusetts (Robert Balk, personal communication, 1941). Nearly a dozen elongate domes with cores of intrusive gneiss appear *en echelon* along the crest of the anticline. The long axis of each dome is slightly offset to the west relative to the dome to the north. The domes occur at irregular intervals, but in general a dome is located approximately every 10 miles.

There are three domes in the eastern part of the Bellows Falls quadrangle. The Alstead dome is entirely within the quadrangle, and the northern half of the Surry dome is in the south-central part. The southernmost tip of the Green Mtn. dome (Chapman, 1942) is exposed along the northern border of the quadrangle at Pierce Brook in Acworth township.

Alstead dome.—The body of the Oliverian magma series that occupies the center of the Alstead dome is 12 miles long and 1 mile wide, extending from Osgood Ledge on the north to 2 miles south of the Ashuelot River on the south. Although the foliation is marked at the margins it is indistinct in the more massive rocks near the center. The bedding and schistosity of the overlying sediments conform to the elongate dome described by the foliation of the igneous core. Surrounding the northern part of the Alstead dome (Pl. 1, map and structure section B–B′) the envelope of metamorphosed sediments is more or less complete. The dips of bedding and schistosity are uniformly outward. The axial planes of the minor folds are

overturned toward the axis of the dome, and the minor fold axes and the stretched pebbles are oriented radially to the dome. Near County School in Acworth the foliation of the gneiss of the Oliverian magma series strikes northeast and dips 10°NW., and in the vicinity of Osgood Ledge the trend is more nearly east-west, and the dips are very gentle to the north. One mile southeast of Cobb Hill the strike is north-south, and the dip is 55°E. Farther south, on the east side of the Alstead dome in the vicinity of Caldwell Pond, the gneiss of the Oliverian magma series intrudes schists that are assigned to the Littleton formation on Plate 1. But the Clough formation is missing here, and it is possible that some of these schists belong to the Partridge formation. At this place the foliation strikes north-northwest and dips 20°E. On Smith Hill in Gilsum township the strike of the foliation is north-south, and the dip is 30°E. At the extreme south end of the Alstead dome the contact between the gneiss and the Partridge formation is covered by glacial drift. At Lily Pond on Surry Mtn., on the west side of the dome, the dips are steeply west. Northward on the west side of the dome the trend of foliation is NNW., and the dips average 45°W. On the west side of the Alstead dome in the vicinity of Alstead Center the contact is a normal fault along which the structural attitude of both the gneiss and the schist is disturbed. In general the foliation is vertical near the fault.

Surry dome.—The tightly folded syncline of the Partridge formation that forms Surry Mtn. separates the Alstead dome from the Surry dome (Pl. 1, structure section C–C′). Reference to the structure contour map (Fig. 4) also shows the extent of the folding. The type of closed folding in this syncline illustrates the squeezing of the sediments between the domes described by Chapman (1939, p. 157) in the Mascoma quadrangle. Along the base of Surry Mtn. on the east side of the Surry dome the foliation of the Oliverian magma series strikes NNW. and dips 60°E. On the west side of the dome east of Mine Ledge the foliation is north-south and vertical; west of Mine Ledge and south of Hancock Peak the foliation of the Oliverian magma series strikes ENE. and dips 20°N.

The northwest flank of the Surry dome is broken by two oblique normal (?) faults, one at Mine Ledge and another a mile to the west. At the boundary between the Bellows Falls and Keene quadrangles, the Surry dome is approximately 4 miles wide, and farther south in the Keene quadrangle the width is greater. The irregular attitude of the foliation within the broad central part of this dome indicates folding and corroborates structural observations made in the Mascoma quadrangle by Chapman (1939, p. 154).

Mode of occurrence of domes.—The dual problem of the age of the gneisses in the domes and the mechanics of this intrusion is an open and inviting question. Billings (1937, p. 535–536) reasoned that the intrusion took place while the sediments were unfolded and that the simple domal structure was preserved throughout the deformation because the mass of gneiss acted as a buttress. This argument is further sustained by the universal cataclastic structure of the gneisses in the domes. In the Moosilauke quadrangle a metamorphosed amphibolite dike was found cutting gneiss of the Oliverian magma series. The intrusion of the gneiss was, therefore, pre-folding.

After considering five hypotheses, Chapman (1939, p. 155) concludes that laccolithic intrusion is the best mechanism because it explains both the foliation of the gneiss and the concentric schistosity of the surrounding metamorphic rocks. According to Chapman's interpretation the cores rose slowly in the doming process, allowing the overlying rocks to deform plastically because of the overload and the upward intrusive push. The schistosity and the foliation were thus formed.

The hypothesis that the various domes are parts of a single folded sheet must, however, be entertained because of the analogy to the structurally associated sill-like Mt. Clough pluton. A hypothesis of a sill intruded from depth upwards from the southeast would also explain the structural asymmetry of many of the domes toward the west. This hypothesis, however, does not explain satisfactorily the concentric schistosity around the domes.

WALPOLE SYNCLINE

General statement.—Between the domes and the Northey Hill thrust the structure contour map (Fig. 4) and the geological map and cross sections (Pl. 1) show a broad shallow syncline 8 miles wide and 15 miles long. Several smaller structural features are superimposed upon this major fold.

Folding.—In a 2-mile-wide belt extending northeastward for 7 miles from the southwest corner of the quadrangle, the bedding and schistosity are horizontal or dip gently. To the east and west of this belt the schistosity and bedding dip inward, describing a syncline with a gentle northeasterly plunge. The structure is simple, and few minor folds are present. Distinctive horizon markers are lacking, and bedding is rare, but wherever both schistosity and bedding were observed they are mutually parallel. In the center of this syncline the lime silicate member of the Littleton formation is preserved. The structure contour map shows that in the northern part of the quadrangle in Charlestown the western limb of this syncline is cut out by the Northey Hill fault.

An oval-shaped outcrop of the Clough formation approximately 1 mile in diameter was outlined one mile northeast of Watkins Hill in Walpole township by pace and compass methods. This is a broad anticline, and its closure is small, the dips around its margins averaging less than 20 degrees.

Farther north the simplicity of the Walpole syncline is modified by a number of "cross folds" that trend northwesterly. The axis of a major "cross syncline", more appropriately called an axis depression, extends from Lily Pond in Alstead township to the village of North Walpole. The southwest limb of this syncline in Alstead and Walpole townships is shown on the geological map (Pl. 1) by the northwesterly trend of two northeasterly dipping beds of quartzite belonging to the Littleton formation. The upper of these two beds crops out in the west branch of Thompson Brook in Alstead township and to the northwest near Slade Cemetery and on Rice Mtn. Throughout this distance it is tightly folded and nearly vertical. A mile south of Cold River the quartzite strikes east-west and dips 25°N. The lower bed of quartzite parallels the upper and extends from the southwest corner of Alstead township to the Connecticut River half a mile northwest of School No. 5. Its circuitous outcrop pattern shows that it is folded and it is irregular in thickness and

continuity. Broad folds are present, but everywhere the dip is to the northward at angles of from 10 to 30 degrees. Minor fold axes and the axes of stretched pebbles plunge northwesterly, conforming to the axis of the larger "cross syncline."

The north limb of this axis depression is defined by the discontinuous quartzite that may be traced from a mile northeast of the village of Alstead to 1½ miles west-northwest of the village of Langdon. The bedding dips and elongated pebbles plunge south at angles averaging 25 degrees. The same bed reappears as a capping on Garfield Hill where it is nearly horizontal indicating that this is approximately on the axis of a "cross anticline" or axis culmination. The continuous but broken belt of quartzite extending from Great Brook to Hemlock Hill and Sams Hill dips north about 20 degrees, and is on the north limb of the culmination.

As portrayed by the structure contours (Fig. 4), both the Surry dome and the Alstead dome die out in anticlines that trend west of north from the major axis of the Bronson Hill anticline. These cross structures in the Bellows Falls quadrangle are not common in western New Hampshire.

Bellows Falls pluton.—The Bellows Falls pluton occupies a major axis depression between the two culminations described above. It is composed of Bethlehem gneiss intruded into the Littleton formation as a sill-like mass. Subsequent erosion has unroofed the sill exposing a basin of orthogneiss conformable with the underlying country rock. The contact, which is believed to be parallel to the foliation of the gneiss and the schistosity of the schist, dips inward everywhere to form the basin. The contact on the south margin dips to the north at angles averaging 30 degrees. Along the west side the dips vary from 30°E. to 60°E. On the northwest the contact is vertical, but it decreases along the north border to dips of 30°W. at the eastern edge of the basin.

From the southeast side a thin septum of schist juts into the basin of Bethlehem gneiss separating it into an upper sill to the northeast and a lower sill to the southwest. The upper and lower sills coalesce at the northwest because the screen of schist is incomplete. The eastern half of the basin is the downthrow side of a vertical fault on the east side of Fall Mtn.

The Bellows Falls pluton has been the object of special study (Kruger and Linehan, 1941). The object was to test the practicability of using seismic methods to determine simple structures in rocks in which elastic waves are transmitted with high velocity. Records of seismic reflections from the bottom contact of the Bellows Falls pluton were taken over sections that had good geological control. The results provided a reasonable check upon the structure interpreted from surface geological data. Seismic evidence indicates that the septum of schist is 1490± feet beneath the surface at the 460-foot bench mark 2 miles west of the village of Alstead. The depth below the surface of the basin at this point according to seismic determinations is 3000± feet. The reflections obtained elsewhere in the pluton were also in accord with the geological data.

It is believed that the Bellows Falls pluton originated several miles to the east as the Mt. Clough pluton. It was intruded as a sill-like mass westward over the Bronson Hill anticline into the present location. Some folding may have followed the intrusion. The Bellows Falls pluton has been detached from its roots by erosion.

Minor igneous bodies.—Two irregular igneous masses occur, one on the east and one on the west side of the Walpole syncline. At Westmoreland Depot a small body of granite about half a mile in diameter is found. On the west side the vertical contact is concordant, but on the northeast side the contact is crosscutting. No regional structural significance is attached to its intrusion. A body of granite 2 miles long and 1 mile wide on Wellington Hill in Westminster township is concordant with the schist on the east side, but part of the west contact is a high-angle fault. A dike of camptonite covering a quarter of a square mile on Prospect Hill, Charlestown, dips gently but irregularly south.

CHARLESTOWN SYNCLINE

The rocks west of the Northey Hill fault have a vastly different structural character from those in the Walpole syncline. The rocks are tightly folded and in many places are thickened 50 to 100 per cent by concordant vein quartz. The fold axes plunge north and south in the same outcrop. The dip of the axial planes and the schistosity range both to the east and west of the vertical (Pl. 2). The outcrop pattern of the Hardy Hill quartzite is typical of this syncline. On Oak Ridge the quartzite is folded into a syncline that plunges south. The belt of Hardy Hill quartzite farther north on Breakneck Hill forms a syncline plunging north. The eastern limbs of both these synclines abut against the Northey Hill fault, and the axis of the Charlestown syncline lies only a short distance west of the Northey Hill fault. It is thus apparent that practically all the strata west of the Northey Hill fault belong to the west limb of the Charlestown syncline. Miniature folding of the type shown by the Hardy Hill quartzite may be observed commonly throughout the west limb of the syncline in outcrops of black schist throughout which are contained paper-thin quartzite layers.

A concordant body of granite 2 miles long and only a few hundred feet wide on the east side of Parker Hill was intruded after the deformation. Consequently it is not granulated and is only weakly foliated. The body pinches out to the north and south. Near the south end of the sill some exposures show an intrusive breccia at the contact. Both the east and west sides of the sill conform to the enclosing metamorphosed sediments which dip steeply to the east.

FAULTS

General statement.—The structure of the Bellows Falls quadrangle is complicated by thrust and normal faults. The Northey Hill thrust has been recognized and mapped, but the Ammonoosuc thrust, which farther north in New Hampshire thrusts low-grade rocks eastward over middle-grade rocks, is believed to be missing in the Bellows Falls quadrangle. Only four of the numerous high-angle normal faults were of sufficient significance to present on the geological map (Pl. 1). These faults are nearly parallel to the regional grain and are post-metamorphism in age.

Northey Hill thrust fault.—Much of the distance from Snumshire to Trapshire the Northey Hill thrust has been traced by pace and compass mapping. For 4 miles south of Trapshire the fault is covered by the Connecticut River valley fill.

From near Bellows Falls the Northey Hill thrust was traced southwestward to Cliff School, Westminster township, where it leaves the quadrangle. Although the faulting is older than the regional metamorphism, it was not difficult to locate in the northern part of the area. The Orfordville formation west of the fault is finer-grained, more quartzose, more graphitic, and more fissile than the schists of the Littleton formation on the east side. The structural discordance on either side of the Northey Hill fault is noticeable. On the geological map (Pl. 1) the Hardy Hill quartzite is truncated by the fault. A bed of quartzite in the Littleton formation on the east side is terminated near the fault. North-south trends with steep dips prevail west of the fault, and east-west trends with gentle dips prevail to the east. Farther south the fault is difficult to trace. The dip of the fault is unknown, but the west side has moved up, and the stratigraphic throw is approximately 10,000 feet.

Mine Ledge fault.—The Mine Ledge fault, characterized by lenses of silicified rock, extends northward along the west side of the Surry and Alstead domes; it may be traced from Mine Ledge over Marvin Hill, along Thompson Brook to Alstead Center. In some zones of brecciation adjacent to the fault the rocks are so intensely fractured that every piece of rock, even of hand specimen size, contains quartz veinlets. Other zones are entirely silicified to a width of 100 feet. The Mine Ledge fault was not seen, but numerous slickenslided surfaces in the wide zone of fractured rock are nearly vertical, so it is presumed that the fault likewise dips steeply. The amount of uplift of the eastern block along this fault is variable from place to place, but the stratigraphic throw averages more than 1000 feet.

Another fault subsidiary to the Mine Ledge fault and parallel to it is marked by silicified zones on Carpenter Hill and to the south in the Keene quadrangle. The west side of this fault moved up.

Fall Mtn. fault.—A normal fault extends along the base of the cliffs on the east side of Fall Mtn. The attitude of the fault was measured on a great slickenslided surface near the hamlet of Cold River where the strike is N. 15°E. and the dip 85°E. The west side moved up, and the greatest stratigraphic throw is 1500± feet.

Other high-angle faults.—High-angle faults of minor displacement occur on Wellington Hill in Westminster township and on the hills west of Dodge Tavern in Walpole township. Along the Wellington Hill fault, which is on the west side of the granite intrusive, the east side was displaced upwards. Considerable silicification has taken place especially at the south end. Some lenses of kyanite which are of hydrothermal origin occur in this silicified zone. Between Dodge Tavern and School No. 5, four fault zones were mapped but do not appear on the geological map. Although two have marked breccia zones, there are no recognizable lithologic differences on either side of the fault which would imply a significant stratigraphic break. Pegmatite along one of these faults contains veins of graphite in which several prospects were opened years ago.

Throughout the west limb of the Charlestown syncline large road cuts reveal numerous zones of intense shearing and crumpling, but the amount of movement is unknown. In the eastern part of the Bellows Falls quadrangle numerous pegmatites

and quartz veins have developed along faults that are associated with folds and show small displacement.

MINOR STRUCTURES

General statement.—In addition to bedding, schistosity, foliation, lineation, and folds, the attitudes of many minor structures were measured. These included incipient schistosity or slip or strain cleavage, joints, and shear stripes.

Two schistosities.—Some schists of the Littleton formation, especially in Westminster and Putney townships in the southwest ninth of the Bellows Falls quadrangle, possess two schistosities. Similar exposures containing two schistosities were found especially in the black schists of the Orfordville formation west of the Northey Hill thrust fault. The earlier schistosity is generally parallel to bedding, and both this schistosity and the bedding are bent into rather simple folds. The later schistosity is approximately vertical and strikes N. 35° W. The intersection of the two schistosities produces a lineation.

The later schistosity is expressed in several ways such as intense crinkling, orientation of minerals, and as a fracture cleavage. In only a few outcrops was it possible to discern new minerals that had crystallized parallel to the later schistosity. Microscopic examination of thin sections, however, showed that micas of the earlier schistosity had been dragged mechanically into the new orientation and that a later generation of micas had grown parallel to the later schistosity. Both phenomena were equally common. This is the shear cleavage described by Mead (1940). In some schists the porphyroblasts of garnet and staurolite had been rotated, and in some a later generation of porphyroblasts had formed parallel to the later schistosity.

Joints.—Cross joints and strike joints (Cloos, 1937, p. 74–75) are most prominent. For figure 5 the poles of the joints were plotted on the lower hemisphere of a Schmidt equal-area net, then contoured; data for 200 joints were used in the preparation of the diagram for the Bethlehem gneiss, and data for 500 joints were used in the preparation of the diagram for the schists. The two main sets of joints are steep, and shallow dipping joints are uncommon. The N. 25° E. strike joints are more abundant than the N. 80° W. cross joints. A comparison of the two diagrams shows that the maxima nearly coincide for the schists and for the Bethlehem gneiss. It can be shown in the field that the same set of joints cuts both the plutonic igneous rocks and the adjoining wall rocks and that the joints extend at least several miles beyond the plutons. Hence the jointing is regional, and it is probably unrelated to the intrusion of the plutons; it is later than the folding and intrusion. Numerous late quartz veins and post-metamorphism dikes follow the main joint sets.

Shear stripes.—In the Walpole syncline, wherever the dip is gentle, large outcrops show stripes of differently oriented micas in the plane of foliation. These are caused by vertical zones of shear which occur in mica schist, quartzite, and granite gneiss. The shear stripes are ¼ to 2 inches wide and are 6 inches to 2 feet apart. In complexly sheared exposures the shear zones are anastomosing, but the most common strike N. 25° E., coinciding with the prominent regional strike joints. Both joints and flexures may occur in the same outcrop. Although these two features appear dis-

similar there may be a genetic relationship. The east block has generally gone up and to the south, although exceptions to this motion were found. The movement in every case is to be measured in millimeters, and in no case does it lead to rupture.

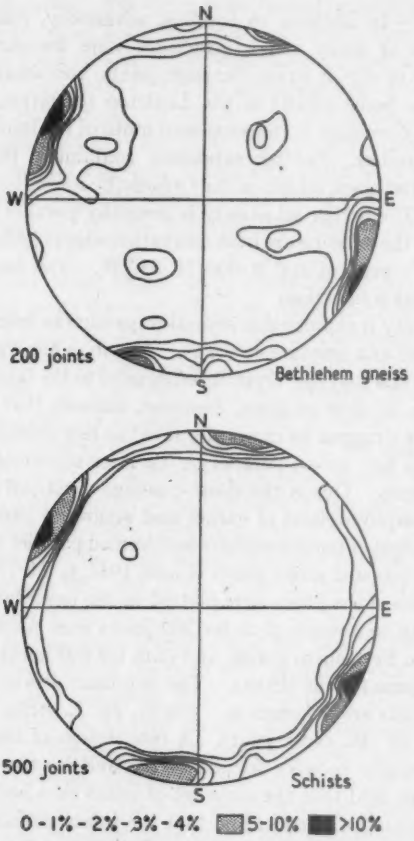

FIGURE 5.—*Contour diagrams of poles of joints in Bethlehem gneiss and schists*
Plotted on equal area net, lower hemisphere

Microscopic study of these stripes in schists shows that a new generation of cross biotites are parallel to these shears.

PROBLEMS IN SEDIMENTATION

Originally the Littleton formation was a very thick arenaceous shale. This constancy in composition suggests a long stable period of marine deposition. Locally in this metamorphosed shale are found two discontinuous coarse conglomeratic quartzites associated with a zone of lime-silicate rocks, which were originally dolo-

mitic sandstones and shales. The special environment that would account for this sedimentary sequence presents a problem.

The lime-silicate member of the Littleton formation on the west limb of the Walpole syncline near School No. 5 is 2000± feet thick, and on the east limb 5 miles to the southeast on the east slope of Barnett Hill the thickness is 1500± feet. In the northern part of the syncline on Garfield Hill in Langdon township the lime-silicate member is about 200± feet thick, too thin to map on the scale of Plate 1. The quartzite beds are widespread, but they are very irregular in thickness. Although the fragments in the quartzitic beds range considerably in size, the coarsest material is in the most westerly outcrops. The conglomerate exposure at Gageville, Westminster township, contains boulders several feet in diameter. These boulders are mostly quartzite, but a few are granite gneiss and schist.

During the lower Devonian this area was unstable. Temporary relative lowering of sea level exposed wide mud flats. On this easily eroded surface extended consequent streams, which occasionally became torrential, gullied irregularly, and obtained huge boulders of pure vein quartz and sandstone either from land sources or reworked stratigraphically lower sandstones. Judging from the size of the boulders, however, a distant land source seems unlikely. The deposition of the thickest and coarsest material was confined to the gully fill, thus accounting for its present sporadic occurrence. Torrential floods of the kind proposed would overflow the gully banks and deposit a thinner sheet of finer debris over a wider area. This would explain the wide distribution. The disconformable relationships developed by such a succession of events would be made unrecognizable by subsequent metamorphism.

METAMORPHISM

GENERAL STATEMENT

The applicability of the zonal concept of metamorphism to New Hampshire was proposed by Billings (1934; 1937) and has been recognized in areas mapped subsequently. In the Bellows Falls quadrangle special study has been given to the variations of the isomorphous minerals under the differing intensity conditions in the three zones, low-, middle-, and high-grade. Over much of the middle- and high-grade zones the rocks are flat or gently folded. Conversely the low-grade rocks have been subjected to intense shearing. This condition implies that an increase in temperature and moving solutions were the cause of the regional metamorphism. Mineralogical data support this.

ZONING

Barrell (1921) compared the New England crystalline province with that of the folded sedimentary rocks in the Appalachians of Pennsylvania. He concluded that neither dynamic metamorphism nor load metamorphism has been as effective in causing the metamorphic change as were the plutonic intrusives. The increase in the intensity of the regional metamorphism in western New Hampshire toward the southeast has been related by Billings (1937) and others to the increase in size and number of intrusives toward the southeast.

The distinction between zones of regional metamorphism were made on the basis of the minerals developed in the aluminous sediments. The index minerals in increasing order of metamorphic intensity are chlorite, biotite, garnet, staurolite, and sillimanite. The appearance of each mineral indicates a zone of higher intensity conditions. The boundaries of these zones are mineral isograds. The low- and middle-grade zones are arbitrarily separated by the biotite isograd, and the middle- and high-grade zones by the sillimanite isograd.

Although all three zones are present in the Bellows Falls quadrangle (Fig. 2) the low-grade rocks are somewhat irregularly distributed. They are found in two areas, one extending from the lowlands of the Connecticut River westward toward Parker Hill in Rockingham township, a second in the valley of the Saxtons River, north of Barbers Park. Middle-grade rocks are found to the west of these areas and eastward to the belt of domes. East of the domes the metamorphism is high grade.

With the exception of the garnet isograd that marks the rise of intensity to the northwest, the metamorphic zones have transitional rather than sharp boundaries. The patchiness of the metamorphism is to be expected because of the multiplicity of the structural, physical, and chemical variables.

An isolated area of high-grade schists comprises the septum in the Bellows Falls pluton. Within the septum the rocks are coarse sillimanite-garnet-muscovite-quartz schists which form a great contrast to the middle-grade garnet-mica schists of the floor beneath the Bethlehem gneiss. This difference in grade of metamorphism for rocks with the same deformational history is compelling evidence for the concept of thermal metamorphism. Likewise to the east the higher-grade schists are intimately associated with the intrusive rocks.

RETROGRADE METAMORPHISM

Retrograde metamorphic minerals are locally conspicuous (Fig. 2). In general the minerals that have undergone retrogression are the porphyroblasts such as biotite, garnet, staurolite, and sillimanite, but on the fringes of the low-grade zone the biotite of the groundmass may be partially reverted to chlorite. The areas of this alteration are erratically located and appear to be independent of structural controls.

MINERALOGY OF ROCKS

The intensity conditions prevailing during metamorphism determine the kind and abundance of minerals that will form in a rock of given chemical composition. The mineralogy of calcareous and lime-silicate rocks of the Waits River and Littleton formations from the middle-grade zone is given in Tables 1 and 2. In these rocks a lack of equilibrium is evident. Incompatible minerals commonly are in contact. Application of the phase rule also shows them to be out of equilibrium. One specimen (Table 1, column 3) contains 11 minerals composed of perhaps 8 oxides in addition to carbon dioxide and water. Disequilibrium rocks are present in all three metamorphic zones. Because the original sediments were rich in alumina all the potash has been used to form muscovite, biotite, or potash feldspar during metamorphism. There is a conspicuous relationship between the abundance of quartz

and the kind of porphyroblast in the rock. Garnet occurs in rocks of all proportions of quartz and mica. The range is from 10 to 98 per cent quartz. Staurolite porphyroblasts are present in rocks containing 2 to 60 per cent quartz. The high-grade rocks containing sillimanite have from 55 to 90 per cent quartz.

TABLE 4.—*Average modes and chemical composition of quartzites and schists recalculated from tables 1 and 2, excluding quartz*

	4 BIOTITE SCHISTS	20 GARNET SCHISTS	12 SILLIMANITE SCHISTS	11 STAUROLITE SCHISTS	78 SHALES*
Mineral Composition:					
Feldspar	10	22	24	3	
Biotite	47	36	38	33	
Muscovite	43	34	25	48	
Garnet		8	5	3	
Sillimanite			8		
Staurolite				13	
Chemical Composition:					
SiO_2	47	49	49	44	53
Al_2O_3	32	30	32	36	23
$FeO + MgO$	9	11	10	10	13
CaO	1	1	1	tr	4
$K_2O + Na_2O$	12	10	10	10	7

* *See* Clarke (1924, p. 33, 631). Recalculated after subtraction of 22.3 per cent quartz.

Inasmuch as all of the rocks studied were oversaturated with quartz, evidently free silica does not affect the equilibrium. For this reason the composition of all of these rocks was recalculated excluding quartz. The specimens were grouped and averaged according to the kind of porphyroblasts they contained. These data appear in Table 4 together with the calculated chemical compositions.

The similarity of the chemical composition of the portion of these schists from which quartz has been excluded has several implications. (1) The present amount of quartz is approximately equal to the original quantity of free silica deposited with the shale, and it has remained independent of the clay fraction of the original shale throughout metamorphism. (2) The similarity of chemical composition of the portion from which quartz has been excluded also suggests that the difference of mineralogy in the various zones is a function of the intensity conditions rather than significant differences in the original composition. (3) It also suggests that little material has been added during metamorphism and that the metamorphism has been thermal.

ISOMORPHOUS MINERALS IN ZONAL METAMORPHISM

General statement.—The rocks in the different metamorphic zones are unlike because of differing physical and chemical conditions. It follows that the isomorphous minerals should likewise show changes in chemical composition in response to modified temperatures and pressures. The process of metamorphism is

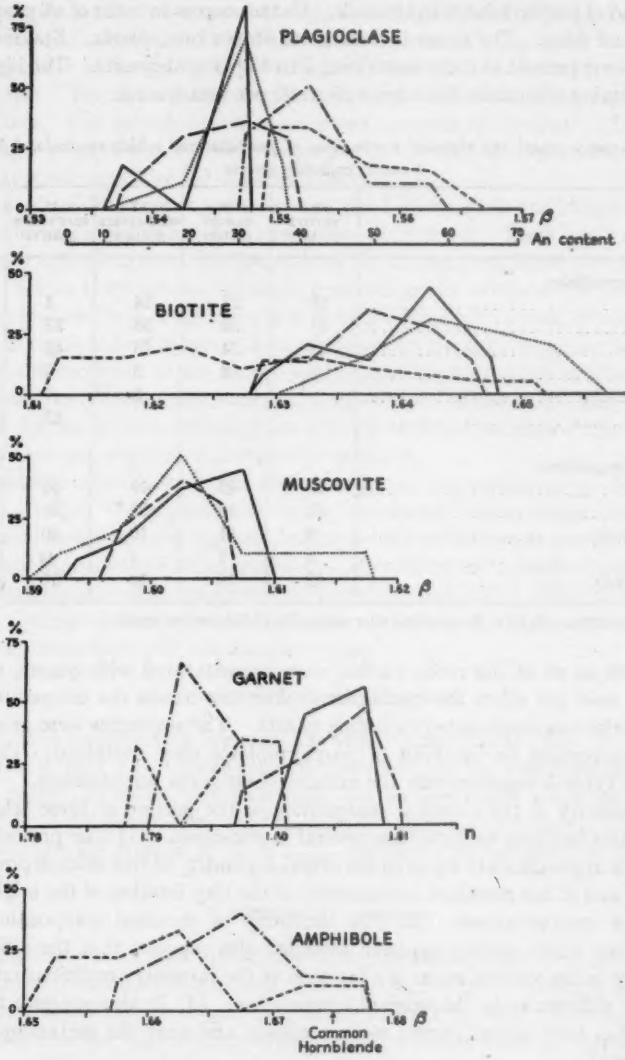

FIGURE 6.—*Indices of refraction of minerals from different rocks*

the reconstitution of minerals to maintain equilibrium, and inquiry into these processes is handicapped because of insufficient data.

Chemical analyses of minerals accompanied by bulk rock analyses are lacking, especially for the metamorphic rocks. This approach is slow and costly, so that optical methods are usually used to determine the composition of some of these minerals.

From the rocks of the Bellows Falls quadrangle plagioclase, biotite, muscovite, garnet, and amphibole were studied. The index of refraction and the specific gravity of garnet were measured. For all the other minerals the β index was determined.

Plagioclase.—The frequency distribution of β of plagioclase is plotted in Figure 6. The most conspicuous features of the curves are the high indices of the plagioclase in the lime-silicate rocks and amphibolites. For these feldspars β averages 1.554 indicating an average content of 40 per cent anorthite. In the middle-grade schists β of plagioclase ranges from 1.536 to 1.548; the average has a composition of calcic oligoclase (An_{27}). For the plagioclase from the high-grade schists β ranges from 1.536 to 1.556, but the average indicates a composition very similar to that of the middle-grade rocks.

Various writers have discussed the albite-anorthite ratio in relation to regional metamorphism. All admit the universality of albite in the low-grade zone. Some believe that in the middle-grade and high-grade zones the anorthite content is a function of the intensity conditions (Phillips, 1930; Ambrose, 1936), and others believe that it depends upon the associated minerals (Turner, 1933; Barth, 1936; Billings, 1937). It is apparent from Figure 6 that the anorthite content of the plagioclase in the middle-grade schists is identical with that of the high-grade schists and injection gneiss. Conversely, the anorthite content of the plagioclase of the middle-grade lime-silicate granulites and amphibolites is higher than that of the high-grade schists. These facts support Turner, Barth, and Billings. If no potential anorthite is present, then albite is stable in higher zones.

Biotite.—In metamorphic rocks biotite is ubiquitous in the middle-grade and high-grade zones, and it is stable under a wide range of physical and chemical conditions. It was believed that the easily determined optical properties of a large number of specimens of biotite from known grades of metamorphism combined with a knowledge of the composition of the rocks might on a statistical basis show significant trends in the metamorphism. Index β was measured for more than 150 specimens and is plotted on a frequency diagram in Figure 6. The optic angle, 2V, is always small and ranges from nearly 0 to 10 degrees.

The curves for biotite illustrate several interesting points. In the lime-silicate rocks β is relatively low. The range is 1.611 to 1.652, and the average is 1.625. Much of this biotite is purplish brown. The biotite from middle- and high-grade quartzites, schists, injection gneisses, and ortho-gneisses has higher indices of refraction, and β averages approximately 1.640. The indices of refraction of biotite from the middle- and high-grade zones are not significantly different. The green biotite typical of the border of the low- and middle-grade zones (Tilley, 1925; 1926; Wiseman, 1934; Billings, 1937) is difficult to study.

Considering all of the rocks, the largest grouping of indices is at 1.640, and although the total range is 1.610 to 1.660 the range of biotite from igneous rocks is 1.600 to 1.722 (Larsen and Berman, 1934). It is apparent from Winchell's (1935, p. 273) variation diagram that the biotite in the schists of the Bellows Falls quadrangle is of intermediate composition, about half way between the phlogopite-eastonite end of the series and the annite-siderophyllite end. It is probable that magnesia causes the lowering of the indices of biotite in the lime-silicate rocks. Hall (1941a) concludes that the chemical composition of biotite cannot be determined precisely from the indices, because iron and titanium commonly substitute for one another and affect the index similarly.

In the rocks of the Bellows Falls quadrangle the distribution of the pleochroic shades of green and red-brown in biotite is spread over both high and low indices and is unrelated to metamorphic zones. Hall (1941b) has shown that the color of biotite depends upon the content of iron, magnesium, and titanium. The green color in biotite is imparted by ferrous oxide, and titania causes the red-brown color. The presence of magnesia masks the coloration caused by titania.

The geological literature contains only 13 analyses of biotite of metamorphic origin. Unfortunately, because many of the analyses are old, only 6 are accompanied by optical data. Fluorine, an important constituent of the mica group, has been determined in only 2 of these analyses. For metamorphic rocks only 4 analyzed biotite specimens have accompanying bulk rock analyses.

Muscovite.—Muscovite is remarkably constant in composition as indicated by the uniformity of β (Fig. 6) and 2V. The peak of the frequency curve of β is about 1.603, and 2V averages 35 to 40 degrees. Muscovite with these properties is similar to that analyzed by Barth (1936, p. 780) which is low in iron and magnesium.

Garnet.—The indices of refraction of garnets plotted on Figure 6 range from 1.785 to 1.815. The garnets from middle- and high-grade schists have an average index of 1.807, whereas those from lime-silicate granulites and amphibolites average lower. Determinations of specific gravity measured on the Berman Density Balance range from 3.92 to 4.20. According to Winchell's garnet diagram (1933, p. 176) the index of refraction and the specific gravity of the garnets of the Bellows Falls quadrangle indicate that they are rich in almandite and spessartite. Borax bead tests made for the garnets of the Bellows Falls area indicated the presence of manganese in every specimen. Other analyzed garnets from schists in New England which have comparable optical properties have a predominance of the almandite garnet molecule.

The evidence concerning composition is similar to that presented by other investigators of regional metamorphism (Tilley, 1926; Barth, 1936; Billings, 1937; Du Reitz, 1938). In some parts of the Bellows Falls quadrangle garnet occurs as porphyroblasts in rocks lacking biotite. Although this at first suggests that garnet in some instances develops under less intense conditions than biotite, it is apparent that biotite has been present, but that the garnet has survived retrograde metamorphism while the biotite has been thoroughly altered to chlorite.

Amphibole.—The frequency curve of β of the amphiboles from lime-silicate granulites and amphibolites shows a range from 1.650 to 1.678 (Fig. 6). The optic angle averages approximately 80 degrees. According to Winchell's curves (1933, p. 252)

these properties indicate approximately 60 per cent of the pargasite molecule ($CaMg_2Si_2O_8$) in solid solution with common hornblende.

Sufficient data were not available to draw conclusions concerning the pyroxene group.

Summary of differences in metamorphic zones.—(1) The plagioclase from the middle- and high-grade schists has little difference in composition, containing an average of 27 per cent anorthitie. (2) For biotite the optics do not indicate any significant differences in composition between the schists in the middle- and high-grade zones. This metamorphic biotite contains 50 to 60 per cent of the iron-rich molecules of annite and siderophyllite. The biotite in the lime-silicate granulites contains more magnesia. (3) In the Bellows Falls quadrangle the muscovite from the three metamorphic zones is constant in optical character, and its composition is nearly that of pure muscovite. (4) Garnet from the high-grade zone tends to have a higher proportion of the almandite molecule ($Fe_3Al_2Si_3O_{12}$) than garnet in the middle-grade zone, but the amount is difficult to estimate. (5) The only statistical optical data for the amphiboles were from the middle-grade zone. These contained approximately 60 per cent of pargasite ($CaMg_2Si_2O_8$). The amphibole in the lime-silicate granulites is richer in magnesia than that in the amphibolites.

ORIGIN OF INJECTION GNEISS

The field evidence that the injection gneiss of the Bellows Falls quadrangle has resulted from mechanical injection rather than chemical replacement is convincing. In many outcrops schistose material may be traced along the strike where it is interlayered with ¼-to 2-inch bands of granitic material forming an injection gneiss perhaps double the thickness of the original schist. This thickness increases in proportion to the amounts of injected material, and this increase in thickness causes contortion of the schist. The intrusive rock is slightly but visibly contaminated by the schist at this stage.

The same process may also be seen on a regional scale. The width of outcrop of the Littleton formation between the Alstead dome and the Mt. Clough pluton in Acworth township is 1½ miles, and in this section there is little injected material. The same stratigraphic section south of Lake Warren in Alstead township is more than 3 miles wide. In this locality the rocks have a similar structural attitude so that the increase in thickness must be ascribed to the numerous injections of Bethlehem gneiss.

In an outcrop the amount of bulge caused by the lens-shaped masses of granitic material is dependent upon the nature of the country rock. Schistose rocks have long thin lenses of injections, and the quartzites have stubby thick lenses.

Microscopic study of the granitic portions of the banded gneiss shows that it closely resembles the Bethlehem gneiss except for obvious and expected contamination by micaceous material.

STRUCTURAL AND METAMORPHIC HISTORY AND CONCLUSIONS

The chronology of the sedimentary, tectonic, and magmatic events in the region is shown diagrammatically in Figure 7. Approximately 20,000 feet of marine

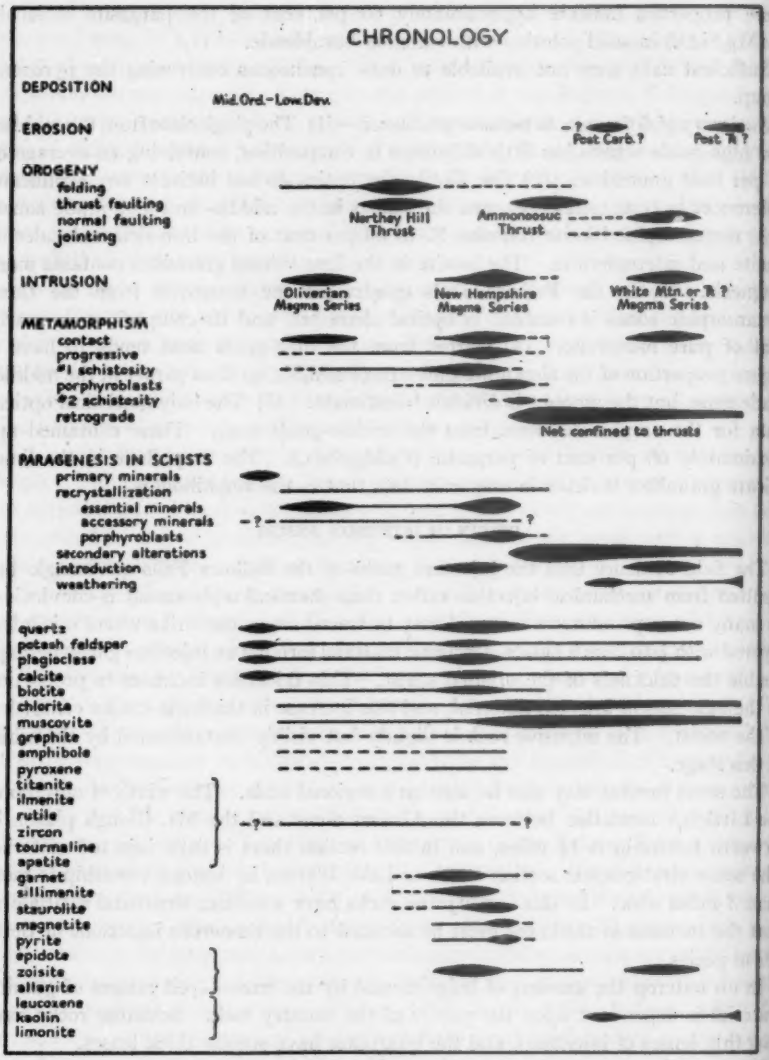

FIGURE 7—*Chronology*

Summarizes relations of deposition, orogeny, intrusion, and metamorphism

sediments, dominantly sandstones and shales, accumulated during parts of the upper Ordovician, Silurian, and lower Devonian periods. In post-lower Devonian time these rocks were intruded by a thick sheet of the Oliverian magma series. The intrusion came into the Ordovician Ammonoosuc volcanics probably from depth

upwards toward the northwest. At the loci of culminations along the axis of the Bronson Hill anticline, domes were eventually formed as folding progressed. Some contact metamorphism as well as the initiation of regional metamorphism also accompanied the intrusion. The main folding was climaxed by thrusting from the west along the Northey Hill fault, which placed the upper Ordovician (?) Orfordville formation in contact with the lower Devonian Littleton formation. During this orogenic activity the thick granitic sheet responded but little to the folding stresses and tended to act as a buttress protecting the flanking sedimentary cover from extreme deformation. In the vicinity of the dome the broad simple folds were maintained, and the planes of weakness parallel to the bedding and schistosity acted as planes of access for a thick sill-like mass of the New Hampshire magma series. A pluton of Bethlehem gneiss rose upward toward the northwest. Later minor stresses continued to re-emphasize the folding on the major axes.

Though a portion of the regional metamorphism preceded the intrusion of the Bethlehem gneiss, the culmination of the progressive metamorphism was coincident with its emplacement. The intensity of the metamorphic zones is spatially related to the intrusives of the Bethlehem gneiss. The attendant hydrothermal activity persisted after the progressive metamorphism, and probably caused some retrograde metamorphic effects.

Subsequently three minor bodies of the New Hampshire magma series intruded the belt of schists west of the domes. Normal (?) faulting of local significance, and jointing on a regional scale preceded the intrusions of the camptonite dikes of the White Mtn. magma series. These post-metamorphism dikes are of negligible importance in the regional tectonics.

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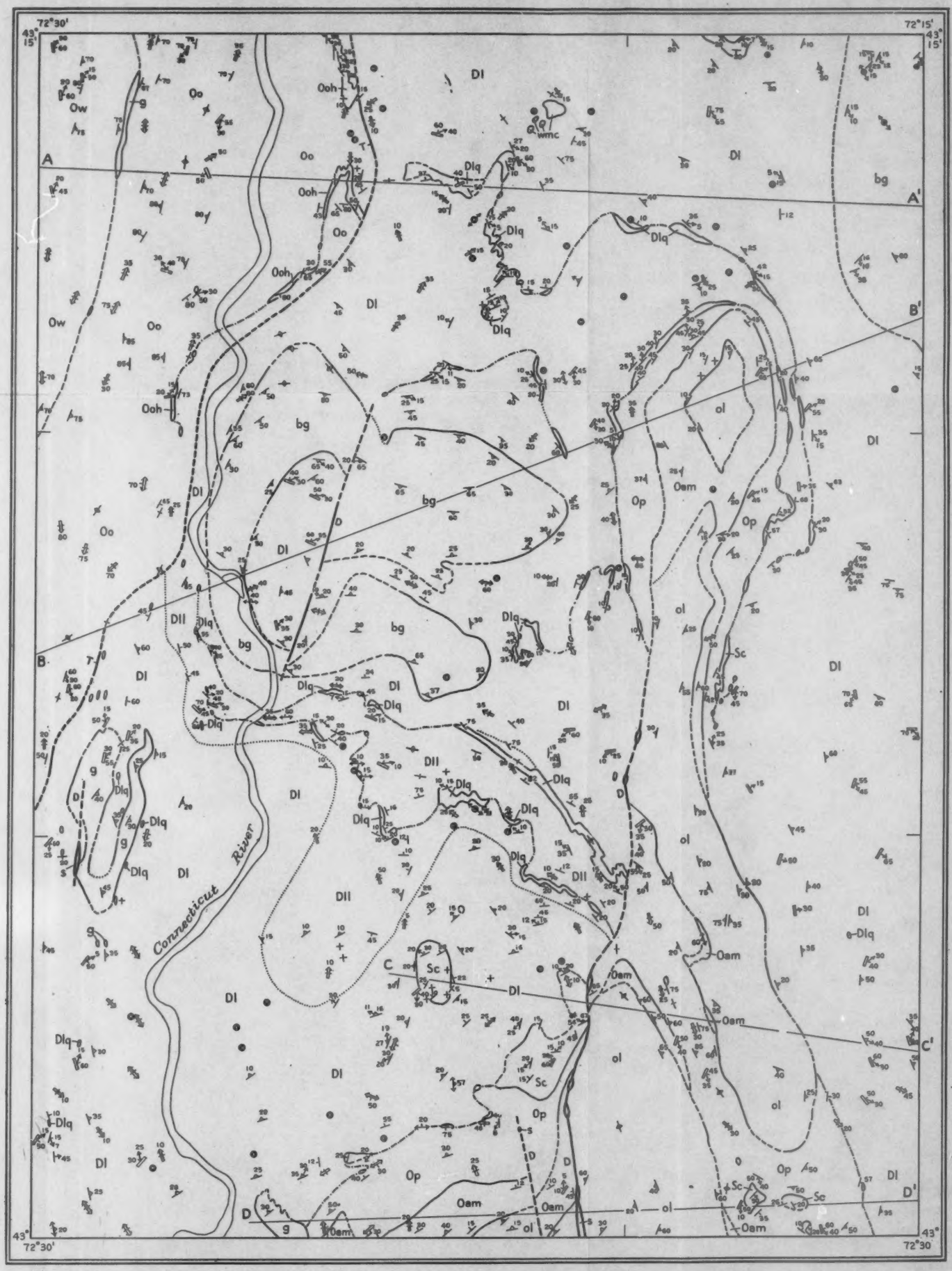
Cerro de Pasco, Perú.

Manuscript Received by the Secretary of the Society, May 18, 1945.



LEGEND

FORMATION SYMBOLS

- wmc – Camptonite – White Mtn. Magma Series
- g – Granite } New Hampshire Magma Series
- bg – Bethlehem gneiss } New Hampshire Magma Series
- ol – Oliverian Magma Series
- Dl – Mica schists } Littleton formation
- Dlq – Quartzites } Littleton formation
- Dll – Lime silicate granulites } Littleton formation
- Sc – Clough formation
- Op – Partridge formation
- Oam – Ammonoosuc volcanics
- Oo – Black schists } Orfordville formation
- Ooh – Hardy Hill quartzite } Orfordville formation
- Ow – Waits River formation
- s – Silicified zone

STRUCTURAL SYMBOLS

- Bedding
- Bedding where horizontal
- Bedding where vertical
- Bedding where overturned
- Bedding and lineation
- Bedding with lineation down the dip
- Bedding and horizontal lineation
- Bedding where horizontal and lineation
- Foliation (schistosity)
- Foliation (schistosity) where horizontal
- Foliation (schistosity) where vertical
- Foliation (schistosity) and lineation
- Foliation (schistosity) with lineation down the dip
- Foliation (schistosity) and horizontal lineation
- Foliation (schistosity) where vertical and lineation
- Foliation (schistosity) where horizontal and lineation
- Fold – strike and dip of axial plane and horizontal projection of axis and value of plunge
- Fold – axis plunges down the dip of axial plane.
- Fold – vertical axial plane and value of plunge of axis
- Fold – strike and dip of axial plane and horizontal axis
- Fold – vertical axial plane and horizontal axis

CONTACTS

- Accurate
- Approximate
- Indefinite, as sharp contact is lacking
- Inferred connection between quartzites

FAULTS

- Normal fault (*D = down-thrown side*)
- Thrust fault (*T = over-thrust side*)

Scale in Miles: 0 1 2 3

TECTONIC MAP

Based on representative geological data

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 57, PP. 207-222, 2 PLS. FEBRUARY 1946

PREGLACIAL HISTORY OF BERMUDA

BY HILARY B. MOORE AND DORIS M. MOORE

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ABSTRACT

Rock cut by dredgers in and around Castle Harbour, Bermuda, has been studied for fossil content. The rock was obtained from depths up to 50 feet below sea level, and much of it was rich in marine fossils. The section is interpreted as a series of beds about 40 feet thick and as representing the record between the post-volcanic period and the formation of the eolianites in the glacial period The possibility that the beds are the result of a rising sea level within the glacial period must also be considered.

The distribution of the species found is reported, and the sequence of the fauna and of the strata suggests that the beds represent a period of shallowing of the sea.

INTRODUCTION

Sayles (1931) has given a complete account of the formation of the land rocks of Bermuda. Briefly, the islands are founded on a chain of volcanic peaks which have a roughly northeast–southwest trend, and which were probably erupted during the

late Tertiary. These peaks were later eroded to a depth of about 250 feet below the present sea level. At some time before the beginning of the Ice Age organic reefs began to form on the table of eroded volcanic material, and with the lowering of the sea level during the Ice Age extensive beaches of calcareous sand were exposed. The high winds of this period blew the sand up into dunes, and the cementing action on these of lime in solution gave rise to the present land rocks. Sayles' work covers mainly the formation of the successive layers of the eolianites and of the interlying layers of soil produced by the decomposition of rock during the interglacial periods.

Unfortunately, from the point of view of the marine history of Bermuda, practically all the surface rock of the islands is eolianite, and in only one or two places is there a small quantity of beach rock. The latter was probably formed at the time of the oldest of the eolianites, and, judging from the fossils which include such typical intertidal forms as *Tectarius* and *Nerita*, is quite comparable with a consolidated form of the sand washed up on the present-day beaches. There is, however, a gap in the known geological history between the volcanic rock and its debris, as described by Pirsson and Vaughan (1913) from a deep boring near Gibbs Hill, and the formation of these glacial eolianites and beach rocks.

During the construction of the American airbase in Castle Harbour and Ferry Reach in 1941–1943, large suction dredgers were cutting rock from as deep as 50 feet below sea level and throwing it up as enormous quantities of broken stone on the newly formed land areas. Much of this rock was very rich in marine fossils. Through the courtesy of the American Army authorities we collected from this material at intervals of about a week throughout the dredging operations. The quantity of the material dredged offered an ideal source for collecting, especially as many of the fossils showed up much more clearly in the newly cut and still wet rock than they did after this had dried out. The only disadvantage was that all the material from the dredge, from whatever depth it was cut, came out mixed. It has therefore been necessary to infer the relative vertical relations of the layers. However, since Castle Harbour is roughly saucer-shaped, when the dredgers were working in the deeper water off shore they tended to cut only the surface layers, whereas when they were close to the shore they were cutting through a much thicker layer of rock, and obviously reaching relatively lower strata. By comparing the material from all localities where the dredgers worked, we feel that it is unlikely that we have made an error in the relative positions of the strata. Obviously cores from a boring would have been desirable as a check, but these were unobtainable. The material was so abundant that probably not many species have been missed, nor a false picture of their relative abundance presented. Many of the base workers collected shells from the dredging grounds, and Mr. Mowbray of the Government Aquarium and Museum also collected fossils, but in no case did we hear of a species being found which we had not recorded. We did not however attempt to collect the more minute recent shells, and in the case of the corals a specialist in the field would no doubt have been able to find more species than we did.

A brief note on this material, which has provided an apparently complete series of marine fossils from the period of erosion of the volcanic rocks up to the present day, has already been published (Moore, 1942). We have insofar as possible sent

a representative series of specimens to specialists for identification and we are greatly indebted to them for their assistance. Owing to the difficulties of war-time work this has not always been possible, and in such cases the identifications are our own. In particular it was hoped that we could include a report on the minerals, but Dr. F. Foreman, who was engaged on this, was called up for army service before it was completed. In the circumstances it was felt that it was best to publish the work in its present form, since it was unlikely that work on the material after the war would greatly modify the general conclusions. The following have kindly undertaken identifications for us: Mr. W. J. Clench, Mollusks; Dr. H. L. Clark, Echinoderms; Dr. T. Wayland Vaughan, Corals; Dr. W. R. Taylor, Algae. Mr. H. C. Stetson has made a preliminary examination of some of the minerals. Dr. J. H. Welsh, Dr. P. E. Raymond, and Dr. Kirk Bryan have given helpful criticism, and Mr. L. L. Mowbray also has helped with both material and suggestions. We should like also to thank Mr. M. D. G. Graham for the photographs. Sets of typical specimens will be available for museums after the war.

TYPES OF ROCK

CLAY

Both reddish-brown and blue-gray clay occurred, in some instances intermingled to some extent. The clay was siliceous and of very fine texture. Mr. Stetson (personal communication) described it as follows:

> "Apparently an ancient soil, possibly reworked, formed at a time when the island did not have its present calcareous cover .... A partial list of the more abundant minerals, all of which might have come from the weathering of basic igneous rocks, is as follows; sphene and apatite are abundant; augite and other pyroxenes are present, although not abundant; there is a considerable quantity of miscellaneous iron oxides rather hard to identify but which might very easily have been derived from altered glauconite."

The consistency of the clay when newly dredged was that of fairly hard putty. It formed the deepest layer found and, though evidently abundant, was not brought up in great quantities since it did not produce good fill. Except for sponge spicules and Foraminifera there were no fossils in the clay.

SECONDARILY REWORKED CLAY

Although most of the clay was of the type described above, some appeared to have been reworked at a later date and mixed with water-worn pebbles of marine limestone; no eolianite pebbles were found, but there was one small pebble of chert. In some samples of this reworked clay there were also a few fossil *Cerithium littoratum* and fragments of *Oculina* spp. These and the pebbles were heavily impregnated with iron. We were not able to decide definitely at what level this reworked clay occurred, but it was probably formed before the first eolianites.

CHERT AND BRICK

Two minerals found had apparently been formed by modification of the clay. It is unfortunate that we cannot give a better mineralogical report on these, since the

presence of the first is of particular interest. There seems to be no doubt, from the intermediate stages found, that both were formed from the clay. The chert (so called for want of a more exact name) was reddish-brown, flintlike material with a conchoidal fracture. It occurred in masses up to about 9 inches in diameter and contained practically no carbonate except minute inclusions. The bricklike material appeared to be clay which had dried to the consistency of brown porous pottery. Both occurred in much smaller quantities than the clay itself.

CLADOCORA ROCK

This rock (Pl. 1, fig. 1), which lay above the clay, formed one of the most characteristic strata. It was a fine-grained calcareous deposit containing a high proportion of fossils, of which the most characteristic was the coral *Cladocora arbuscula*. The latter was unbroken and appeared to have been infiltrated *in situ* by a fine calcareous mud which had later been indurated to form a hard rock, though frequently leaving considerable cavities. The fine texture of the rock, the absence of any large sand grains in it, and the absence of either littoral species or massive reef corals suggest that it was formed in moderately deep water, and before there were any beaches in the neighborhood to contribute coarse particles to it. The *Cladocora* rock lay too deep to be reached in much of the area, but, where the dredges cut into it, it was very abundant. Its rich fossil content has probably provided a fairly complete picture of the characteristic fauna of the period.

OCULINA ROCK

The texture of the *Oculina* rock (Pl. 1, fig. 2) was similar to that of the *Cladocora* rock, and it was probably formed under similar or slightly shallower conditions. It lay next above the *Cladocora* rock and is characterized by the corals *Oculina pallens* and *O. varicosa*. Though abundant in some of the dredgings, it was less so than the *Cladocora* rock. The two were distinct and rarely intergraded; in fact less than 1 per cent of the *Oculina* rock examined also contained *Cladocora*.

UNDATED OLD ROCK

Some fossils found in fine-textured rock, but with no key corals attached, have been referred to undated old rock but were presumably from either the *Cladocora* or *Oculina* rocks. We have ascribed to this rock some of the earliest of the massive corals, *Montastraea* and *Dichocoenia* spp. These were strongly recrystallized and in some cases infiltrated with gray mud, the fine texture of which makes it unlikely that they belonged to the sandstone period when the reef corals became really abundant. Probably they stood up as isolated masses above the general level of the bottom and so escaped inclusion in the consolidated beds of branching corals.

SANDSTONE

This calcareous sandstone (Pl. 2, fig. 1) was much coarser than either of the older rocks and looks as though it was formed by the partial cementing of particles similar

FIGURE 1. CLADOCORA ROCK x 1.2

FIGURE 2. OCULINA ROCK x 1.2

BERMUDA ROCKS

FIGURE 1. SANDSTONE, SHOWING COARSE TEXTURE AND NUMEROUS SHELL FRAGMENTS x 1.2

FIGURE 2. BRACHYDONTES ROCK, SHOWING BRACHYDONTES EXUSTUS AND LAMPANELLA MINIMA x 1.2

to those now found in Castle Harbour sand. It lay above the *Oculina* rock and immediately below the loose sand forming the present bottom of Castle Harbour and Ferry Reach, except in those localities where beach rock was interpolated. From its fossil content and coarse texture, this appeared to have been a shallower-water formation than the preceding ones and was probably formed in lagoons similar to those now overlying it. However, from the absence of key littoral forms such as *Lampanella minima* it seems to have been definitely neither a shore deposit nor one lying very close to the shore. It must have been a sandy bottom, covered at times by large numbers of tubular sponges. In Ferry Reach it showed evidence of local dense growths of *Oculina* spp. at one period, but here the rock had been so intensively recrystallized that the corals cannot be identified with certainty. Sandstone was considerably more abundant than either of the preceding rocks, though this was no doubt due, at least in part, to its having been reached by the dredgers more frequently than the deeper lying strata.

LOOSE SAND

This loose mixture of coarse fragments of shells, polychaete tubes, corals, algae, and so on requires no special description. It cannot be dated except insofar as it lies above the sandstone. Although some of it is being produced at the present time, the shells in it indicate both by their species and by their relative abundance that considerable faunal changes have taken place during the period of its formation. In the list of species (Table 1) all forms found in this loose sand have been described as recent. Here again the absence of such typically littoral forms as *Lampanella*, *Tectarius*, and *Echinella* shows that the littoral contribution to the sand was very slight.

The above series of clay, *Cladocora* rock, *Oculina* rock, sandstone, and loose sand seems to represent the general sequence, but in places there were other deposits; these were of littoral origin, and their exact level has not been determined. Except possibly for the shell conglomerate, they probably came in at about the sandstone or loose-sand period. All were of local occurrence only, and not very abundant.

SHELL CONGLOMERATE ROCK

This was composed almost entirely of lamellibranch shells which had been so eaten away by boring sponges that the species were unrecognizable. The interstitial rock was slightly coarser than the *Oculina* rock but much finer-grained than the sandstone, and this, together with the presence of occasional fragments of *Cladocora* and *Oculina*, suggests that it was part of one of the older and deeper-water deposits. In many cases it included a large number of mineralized oval faecal pellets.

MANGROVE PEAT

This was typical peat similar to that found among mangroves at the present time. It was mainly vegetable in origin, with some admixture of fine-grained calcareous mud or sand, often in layers. There were usually no shells in it.

TABLE 1.—*List of species*

vc—very common, c—common, fc—fairly common, f—few, r—rare, n—none

	det[1]	*Cladocora* Rock	*Oculina* Rock	Undated Old Rock[2]	Sandstone	Recent	Notes
Coelenterata							
Millepora alcicornis L.	T.W.V.	fc	f	—	n	c	Some fossils very massive.
Cladocora arbuscula Les.	T.W.V.	vc	r	—	n	n	
Oculina pallens Ehrenb.	T.W.V.	r	c	—	n[3]	n?	
O. varicosa Les.	T.W.V.						
O. diffusa Lam.	T.W.V.	?	?	?	?	c	May have occurred as fossils but not been identified.
O. valenciennesi M. Edw. & H.	T.W.V.						
O. sp.	T.W.V.						
Porites porites (Pall.)	T.W.V.	f	f	—	c	fc	
Siderastraea siderea (Ell. & Sol.)	T.W.V.	fc	fc	—	c	fc	
Montastraea cavernosa (L.)	T.W.V.	r	n	—	c	r	
M. annularis (Dana)	T.W.V.	n	n	—	fc	n	
Dichocoenia stokesi (M. Edw. & H.)	T.W.V.	one	n	f	fc	n	
Meandrina meandrites (L.)	T.W.V.	one	n	n	fc	f	
Meandra cerebrum (Ell. & Sol.)		n	n	—	n	c	
M. labyrinthiformis (L.)		n	n	—	n	c	
Isophyllia sinuosa (Ell. & Sol.)	T.W.V.	n	n	—	c	c	The sandstone form is more foliate than the recent.
Agaricia fragilis Dana		n	n	—	n	fc	
Mollusca							
Arca secticostata Reeve	W.J.C.	fc	n	—	fc	c	
A. occidentalis Phil.	W.J.C.	n	n	—	n	fc	
A. umbonata Lam.	W.J.C.	fc	fc	—	r	fc	
A. candida Gmel.	W.J.C.	fc	fc	—	r[4]	fc	Confused with *A. umbonata*, so distribution doubtful.
Pinna rudis L.	W.J.C.	n	n	f	fc	f	
Pteria colymbus Roeding		fc	two	—	fc	fc	

Pinna rudis L.	W.J.C.	n	n	f	fc	f	
Pteria colymbus Roeding		fc	two	—	fc	fc	
Pinctada radiata Leach	W.J.C.	n	n	—	n	f	
Isognomon alata Gmel.	W.J.C.	n	n	—	n[5]	c	Local.
Ostrea frons L.	W.J.C.	r	r	—	fc[4]	fc	Up to 9 by 10 cm.
O. virginica Gmel.	W.J.C.	n	n	—	n	fc	
Spodylus echinatus Martyn	W.J.C.	c	r	—	r	vc	Recent up to 19 by 16 cm.
Plicatula gibbosa Lam. (= *P. plicata*)	W.J.C.	vc	vc	—	f[4]	n	
Pecten ziczac L.	W.J.C.	n	n	—	one	fc	Recent very large.
P. imbricatus Gmel.	W.J.C.	n	n	—	n	fc	
P. muscosus Wood	W.J.C.	n	n	—	n	fc	
P. gibbus L.	W.J.C.	fc	r	—	c	fc	
P. nodosus L.	W.J.C.	n	one	—	n	r	
Lima lima L.	W.J.C.	n	n	—	n	f	
L. hians Gmel.	W.J.C.	n	n	—	n	r	
Anomia simplex Orb.	W.J.C.	n	n	—	n	f	
Brachydontes exustus L.	W.J.C.	n	n	—	two[4]	f	
Modiolus tulipus L.	W.J.C.	n	n	—	three	fc	
Lithophaga nigra Orb.	W.J.C.	one	n	fc	fc	fc[6]	
Chama macrophylla Gmel.		fc	one	—	fc[4]	c	
C. congregata Conrad		c	c	—	n	vc	
Lucina pennsylvanica L.	W.J.C.	n	n	fc	fc[4]	n	
Codakia orbicularis L.	W.J.C.	n	n	one	vc[4]	c	
C. orbiculata Mont.	W.J.C.	n	n	—	n	fc	
C. costata Orb.	W.J.C.	f	n	—	n[4]	fc	Identification of fossils doubtful.
Loripinus edentula L.	W.J.C.	c	f	—	fc	fc	
L. schrammi Crosse	W.J.C.	n	n	—	n	fc	
Laevicardium serratum L.	W.J.C.	two	n	f	fc	vc	Some fossils very large.
Macrocallista maculata L.	W.J.C.	one	n	fc	fc	n	
Venus cancellata L.	W.J.C.	one	n	c	c[4]	n	
Coralliophaga coralliophaga Gmel.	W.J.C.	n	n	—	n	r	
Tellina interrupta Wood	W.J.C.	n	n	—	n	fc	
T. laevigata L.	W.J.C.	n	n	—	one	r	
T. ?radiata L.		n	n	—	n	f	

TABLE 1.—*Continued*

	det[1]	*Cladocora* Rock	*Oculina* Rock	Undated Old Rock[2]	Sandstone	Recent	Notes
Mollusca—*Continued*							
T. fausta Don	W.J.C.	n	n	—	one	fc	
T. magna Spengler	W.J.C.	n	n	—	n	fc	
Apolymetis intastriata Say	W.J.C.	fc	n	—	fc	fc	
Semele proficua Pult	W.J.C.	n	n	—	n	fc	
Tagelus gibbus Spengler	W.J.C.	n	n	—	n	fc	
Diadora cayenensis Lam	W.J.C.	fc	r	—	r[4]	r	
Fissurella barbadensis Gmel	W.J.C.	n	n	—	n	f	
Emarginula cancellata Gmel	W.J.C.	one	n	—	n	one	
Livona pica L	W.J.C.	n	n	—	fc	fc	
Astraea longispina Lam	W.J.C.	n	n	—	one	fc	
Nerita versicolor Lam	W.J.C.	n	n	—	two	one	
N. tessellata Gmel		n	n	—	n	one	
Natica canrena L	W.J.C.	f	f	—	fc	c	Local.
N. livida Pfr	W.J.C.	n	n	—	n	f	
Polynices lactea Guilding	W.J.C.	n	n	—	n	r	
Xenophora trochiformis Born	W.J.C.	n	n	—	n	r	
Littorina angulifera Lam		n	n	—	n	one	
Tectarius ?trochiformis Dillwyn		n	n	—	one	n	
T. muricatus L		n	n	—	n	one	
Vermetus spirata Phil	W.J.C.	n	n	one	n	c	
V. sp		fc	one	—	n	n	A smaller form, not colonial.
Modulus modulus L	W.J.C.	n	n	—	n	fc	
Cerithium littoratum Lam	W.J.C.	fc	fc	—	fc[4]	c	
C. minimum Gmel. (= *Lampanella minima*)	W.J.C.	n	n	—	n	r[5, 6]	
C. muscarum Say	W.J.C.	n	n	—	n	f	
Strombus costatus Gmel	W.J.C.	fc	fc	—	fc	fc	
S. gigas L	W.J.C.	n	n	—	n	fc	Local.
S. pugilis L		n	n	one	four	n	
Cyphoma gibbosa L		n	n	—	n	r	
Cypraea cinerea Gmel	W.J.C.	n	n	—	n	f	

S. pugilis L.		n	n	one	four	n	
Cyphoma gibbosa L.		n	n	—	n	r	
Cypraea cinerea Gmel.	W.J.C.	n	n	—	n	f	
C. exanthema L.	W.J.C.	one	n	f	fc	c	Recent adults 4.6–.2.4 cm.
C. spurca L.	W.J.C.	n	n	—	n	r	
Trivia quadripunctata Gray		n	n	—	n	fc	
Tonna perdix L.	W.J.C.	n	n	—	n	fc	
Cymatium femorale L.	W.J.C.	n	n	—	n	f	
C. aquitile Reeve	W.J.C.	one	n	one	n	c	
C. chlorostoma Lam.	W.J.C.	n	n	—	n	f	
C. cynocephalum Lam.	W.J.C.	n	n	—	n	f	
C. tuberosum L.	W.J.C.	n	n	—	n	fc	
C. costatum Born	W.J.C.	n	n	—	n	two	
Charonia tritonis Conrad	W.J.C.	n	n	—	one	fc	
Murex pomum Gmel.	W.J.C.	n	n	—	f	r	
Thais deltoidea Lam.	W.J.C.	n	n	—	two	r	
Coralliophylla abbreviata Lam.	W.J.C.	n	n	—	n	four	
Cantharus tinctus Conrad		n	n	—	n[4]	fc	
Pyrene mercatoria L.	W.J.C.	n	n	—	n	fc	
Nassa ambigua Mont.	W.J.C.	n	n	—	n	f	
Fasciolaria tulipa L.	W.J.C.	n	n	—	fc	n	
Leucozonia cingulifera Lam.	W.J.C.	one	n	—	one	r	
Oliva reticularis Lam.	W.J.C.	n	n	—	f	r	
Conus agassizi Dall.	W.J.C.	n	n	—	one	fc	
Bulla occidentalis Adams	W.J.C.	two	n	fc	c[4]	c	
Umbraculum sp.		n	n	—	n	one	
Melampus coffeus L.	W.J.C.	n	n	—	n	one	
Echinodermata							
Eucidaris tribuloides (Lam.)		n	n	—	n	r	
Centrechinus antillarum (Phill.)		n	n	—	n	r	
Lytechinus variegatus (Leske)	H.L.C.	n	n	r	n	f	
Echinometra lucunter (L.)	H.L.C.	f	n	f	n	f	(Spines fc. in older rocks.)
Leodia sexiesperforata (Leske)	H.L.C.	n	n	—	one	n	
Moira ?atropos (Lam.)	H.L.C.	n	n	—	three	n	

TABLE 1.—*Continued*

	det[1]	*Cladocora* Rock	*Oculina* Rock	Undated Old Rock[4]	Sandstone	Recent	Notes
Porifera							
Sp. A[7]		fc	fc	—	fc	fc	
Sp. B[8]		n	n	—	c	f?	
Arthropoda, Crustacea							
Brachyura spp.		one	n	three[9]	one	f	
Vertebrata[10]							
Algae							
? Lithothamnion incertum Foslie	W.R.T.	n	n	—	f	f	Identification tentative.

1. T.W.V. = Dr. T. Wayland Vaughan; W.J.C. = Dr. W. J. Clench; H.L.C = Dr. H. L. Clark.
2. Records for undated old rock are included only when necessary for amplification of the record in the other columns.
3. *O.* sp., probably *O. falkes*, was common in sandstone in Ferry Reach.
4. Present in *Brachydontes* rock.
5. Present in *Isognomon* rock.
6. Probably other borers were present but not collected.
7. A sponge boring in mollusk shells.
8. A sponge, found only as a cast, and resembling the recent *Pallispongia vaginalis*.
9. *Mesippe* sp., probably *M. mercenaria*.
10. One turtle bone was found in secondarily reworked clay, and a few fragments of whale bones in recent deposits.

ISOGNOMON CLAY

This slightly peaty calcareous clayey mud contained masses of bedded shells of *Isognomon alata*. As this oyster is common at the present time on the roots of mangroves, the deposit was probably made in a mangrove swamp to which the sea had sufficient access to bring calcareous mud in considerable quantity.

ISOGNOMON ROCK

Similar to the *Isognomon* clay but hardened by cementing into solid rock, this rock was found in only one place, in Ferry Reach, and there not in great quantity.

LAMPANELLA CLAY

This clay was similar in texture to the *Isognomon* clay, but with the gastropod *Lampanella minima* as its dominant form. As this species now occurs in enormous numbers between tide marks and in shallow pools, it is clear that the deposit must have been formed in such a locality, and one in which calcareous mud would accumulate. A few *Lampanella* were occasionally found in the *Isognomon* clay, but the two species did not intergrade.

BRACHYDONTES ROCK

This was a fairly coarse-textured rock (Pl. 2, fig. 2), obviously of littoral origin. The littoral mussel *Brachydontes exustus* was common in it, as was also the gastropod *Lampanella minima*. It appears to be a cemented form of a deposit similar to the *Lampanella* clay, but with *Brachydontes* added. All stages of gradation between this and *Isognomon* rock were found. Like the latter it was a scarce rock, and found only in part of Ferry Reach.

DISCUSSION

The previously known geological history of Bermuda has a gap between the period when weathering of the volcanic core was complete and the glacial period when sand beaches appeared and their materials were blown into sand dunes which gave rise to the present land rocks. The series of deposits described in this paper commences with a clay formed from weathered volcanic rocks; it continues through *Cladocora* rock, *Oculina* rock, and sandstone, all of which were found to underlie the eolianites; it finishes with loose sand laid down during a period from the commencement of the formation of the eolianites to the present day. The recrystallization of the sandstone in Ferry Reach, and perhaps also the cementing which has taken place in all the solid rocks, seems to indicate a period of elevation above sea level, whereas the occurrence of now-submerged beach rocks—*Isognomon* and *Brachydontes* rocks—indicates a period when sea level was lower than at present.

No fossils other than micro-organisms were found in the clay, and certainly there was no abundant coral growth when it was formed, as there was in the succeeding *Cladocora* period. There would also appear to have been no beaches or other sources of calcareous sand in the neighborhood. This indicates that the clay layer was

formed either below the depth at which corals begin to build up a reef or in water too cold for the corals to grow. The latter is of course quite possible, but the order of appearance of the various forms, and particularly the corals, in the successive strata, is indicative of steadily shallowing conditions, so that it seems simpler to extrapolate these changes of depth to cover the clay period also, rather than to assume changes of temperature. Gardiner (1931, p. 64) says... "If we summarize all field observations, we are driven to conclude that the maximum depth from which corals would commence to form a reef is approximately fifty fathoms, while a suitable environment in such a depth for the growth of corals to form a reef can only be found on banks in the clearest waters of the open ocean." Such conditions of very clear water certainly obtain at the present time around Bermuda.

Between the *Cladocora* rock and the recent sand, the sequence from deeper to shallower water is clear. The steady coarsening of the texture of the sediment forming the rock has already been referred to. Of the corals, *Cladocora* is dominant in the first and oldest layer and is next replaced by *Oculina* spp. Massive corals are, however, very rare in both formations. At the third level, the sandstone, the reef-forming corals *Montastraea* and *Dichocoenia* become common, but the present-day *Meandra* spp. are absent and do not appear until the latest formation. Incidentally *Montastraea* and *Dichocoenia* are now restricted in general to the outer reefs where the surf is heavy, whereas *Meandra* is characteristically abundant on the protected reefs inside the lagoons, of which Castle Harbour is an example. This suggests that the sandstone formation was produced at a time when the reefs were approaching the surface but before the surf had been reduced by other reefs forming a protecting barrier farther seaward. The same story is indicated by the echinoderms. *Moira ? atropos*, which occurs only in the sandstone, has a bathymetric range of only 0–80 fathoms, whereas *Lytechinus* and *Echinometra*, which are common in the earlier formations, have ranges of 250 and 300 fathoms respectively (Dr. H. L. Clark, personal communication). The mollusks of the older rocks do not include any characteristically deep water forms, but they do show clearly the absence of characteristically littoral ones. For example, *Brachydontes* is abundant in the beach rock, but only two specimens were taken in the sandstone, and none from older strata. The sandstone also yielded only two specimens of *Nerita* spp., and one of *Tectarius*, and neither was found in older rocks. Again, *Lampanella*, the most abundant and typical of the littoral forms, was found only in beach rock, and *Littorina* not at all. The steady shallowing of the water in which the successive deposits were formed is thus clear. After the now-submerged beach rocks were formed, there must have been a rise in sea level, possibly one of those mentioned by Knox (1940) in his account of the peat deposits in Hamilton marsh. The depth at which the clay was deposited is, however, uncertain. It was presumably formed at a depth too great for coral growth, which may be put at anything greater than 30–40 fathoms (180–240 feet). Sayles gives the sea level in the late Tertiary period as 85–170 feet above its present level, which would put the clay at 125–210 feet below the highest late Tertiary sea level. This would probably have been too deep for coral growth.

The whole period between the clay and the present loose sand or beach rocks is represented by a column of less than 40 feet. This thickness presumably represents

the amount by which the surface built up during the long period of fluctuating sea level during the Ice Age, including the additional deposition of some sand in post-glacial times. There must have been periods during the Ice Age when all the strata under consideration were elevated above sea level, since at the height of the Ice Age the sea stood about 262 feet below its present level (Daly, 1929). If any deposits were made in the Castle Harbour area during these episodes of low sea level, we have found no trace of them, but it is quite likely that they were loose sand which later blew or washed away. Possibly it was during this period of elevation that the cementation took place which transformed the mud and sand filling of the *Cladocora*, *Oculina*, and sandstone strata into rock.

The question of the history of Bermuda in the period immediately following the eruption of the volcanic peaks is, in the light of present knowledge, somewhat more complicated than would appear from Sayles' paper. In the boring made near Gibbs Hill (Pirsson and Vaughan, 1913), weathered volcanics were found at 245 feet below sea level, and undisturbed volcanic rock at 560 feet. Woollard and Ewing (1939), by seismic sounding, placed the volcanic rock, presumably undisturbed, at 243 and 273 feet in the Ferry Reach neighborhood. We found clay of volcanic origin at about 40 feet in the Castle Harbour area and were informed that dredgers also found it at a similar depth in a considerable area inside the northern reefs. It is therefore probably widely distributed. Woollard and Ewing's data agree with Sayles' suggestion of a volcanic table at a depth of about 250 feet below present sea level, and according to him this is a depth to which it might be expected to have been cut by wave action in the period of elevated sea level of the late Tertiary. There must, however, have been extensive peaks left above this level to provide the material which later built up to, and formed, the blanket of clay now lying 40 feet below sea level. There may, of course, be eolianites between this clay and the volcanic rock in the Castle Harbour area, since the Gibbs Hill boring showed them down to 245 feet, but at any rate this widespread clay layer indicates the existence of considerable exposed volcanic rock at the time it was formed, and at a time when the sea level was some 200 feet higher than at present as argued from the absence of coral growth. If, however, the absence of corals was due to the water being too cold, then such an elevation need not be assumed.

Two theories may be suggested to cover the known facts, although there is not sufficient information at present to show whether either of them is correct, as the fossils found have not yielded specific information as to geologic dates. According to the first theory, a shelf was cut at about 250 feet below sea level but left some considerable peaks. This happened before the high sea level of the late Tertiary period, and it was during the latter that the remaining peaks were eroded until their debris covered the shelf up to the level of the clay now found at 40 feet. Possibly some of the craters mentioned by Woollard and Ewing did not fill in completely, and it was into one of these, later filled in by eolianites, that the Gibbs Hill boring was made. As long as the high sea level persisted, the clay lay too deep for coral growth, but with the subsequent drop in level corals appeared and gradually built up the series of strata described in this paper. With the further drop in sea level during the glacial period, these strata were raised above sea level, and the process of cement-

ing them into solid rock took place. The weakness in this theory lies in the assumption that the Gibbs Hill boring was made in a locality which was not typical of the area as a whole.

An alternative theory is that the 250-foot platform was cut in late Tertiary time, as suggested by Sayles, though with some peaks remaining. The earliest glacial eolianites, which according to Sayles are not represented above sea level, built this up during the very low sea level of the period, nearly to the level of the clay, and the latter was deposited during a phase of the early glacial period when the remaining peaks were still being eroded. It must have been during an interglacial period, when the sea level was the same as at the present time or higher, that all the strata described here were formed. Later phases of the glacial period then produced the land eolianites which were shown to overlie them. This theory also is open to serious objections. It would be surprising if so disproportionately thick a layer of eolianite could have been formed in the earliest part of the glacial period, and, according to Sayles, only the Nebraskan, or part of it, is unrepresented above sea level. It also seems rather unlikely that all the strata described here—clay, *Cladocora* rock, *Oculina* rock, and sandstone—could have been formed in a single interglacial period. Further, the clay might have been expected to include more calcareous fragments had any eolianites been present in the neighborhood when it was laid down. On the whole it seems more likely that the fossil fauna described here is preglacial. That it could have survived the glacial period is shown by the fact that the sandstone fauna was certainly in existence before the period of formation of the land eolianites and yet was so similar to that of the present day that it is highly unlikely that it became extinct and was reintroduced.

The fauna shows considerable changes in the successive strata, some undoubtedly associated with changes in the nature of the habitat, and others probably representing the successive arrival of new forms to colonize the area. The steady increase in the number of species points to the latter circumstance. We have already discussed the changes in the coral fauna, and these may well be associated with changing conditions. Two of the corals, both of which were common during part of the time, namely *Cladocora* and *Meandrina*, have become almost extinct and very rare, respectively, in Bermuda. Among the mollusks, a number of the lamellibranchs were not found until the coarse sand appeared, as might be expected from the nature of their normal habitat today. The same is true of the echinoderm *Moira ? atropos*, which is not now known to be living in Bermuda but may well have been missed by collectors, as it is common in the West Indies. Some of the mollusks which were common in the earlier formations became rarer later; a good example of this is *Plicatula plicata*. This species, if present at all in Bermuda today, is restricted to deep water. The species of *Strombus* also show a marked change from the dominance of *S. costatus* throughout the fossil period and into the loose sand, to its replacement by the present *S. gigas*. In addition, many species have either died out or become very scarce in the Castle Harbour area although still occurring elsewhere in the islands. For example we have never taken a live *Cypraea* in the area, and yet *C. exanthema* must have been very common there at times, and two other species of this genus occurred. It is interesting also to note that several species formerly grew much larger than they do now. Particular examples are *Pecten ziczac* and

Ostrea frons, some of the fossil examples of the latter being so large that Mr. Clench expressed his doubt as to their specific identity with living forms.

The first community, represented by the *Cladocora* rock association, was dominated by huge beds of the branching coral *Cladocora arbuscula*. Along with this were occasional small patches of *Porites*, *Millepora*, and *Siderastrea*, and growing on the corals were *Chama* spp., *Spondylus*, *Plicatula*, and *Arca umbonata*. There were also fair numbers of *Diadora alternata*, *Cerithium litoratum*, and *Vermicularia* sp., although the latter never formed the massive colonies found today. There must have been clear areas of muddy bottom among the coral, where *Loripinus edentula* was abundant, and where *Pecten gibbus* and *Strombus costatus* were common. The Cymatiums and Cypraeas, however, which later became so common, were still rare or absent. The urchin *Echinometra* also appears to have been fairly common among the coral.

The transition to the period of the *Oculina* rock was sharp. Bottom conditions were much the same, as dense tangles of branching coral were interspersed with patches of clear mud, but the dominant corals were *Oculina* spp. Otherwise the fauna seems to have been much the same as in the *Cladocora* period except for the slight increase in massive corals such as *Montastraea* and *Dichocoenia*. Some of the lamellibranchs also had become more common, *Pinna*, *Macrocallista*, *Chione*, and *Codakia* in particular.

In the sandstone period there was a big change in conditions. Massive corals were now common, although the recent Meandras had not yet appeared. *Oculina* spp. had disappeared in most of the area, but *Porites* and *Siderastrea* were fairly common. Most of the bottom must have been a sand of much coarser texture than the preceding muds. Most of the mollusks that had been present in the earlier periods continued to live, and a number of new ones appeared. *Codakia orbicularis*, of which only one earlier specimen was found, became common, although the smaller *C. costata* had occurred in small numbers since the *Cladocora* period. *Loripinus edentula* and *Pecten gibbus* were both fairly common also, and locally the latter occurred in enormous numbers. A number of gastropods such as *Livona*, *Fasciolaria*, *Murex*, *Charonia*, and *Oliva* appeared for the first time. One very striking feature of the sand areas was the heavy growth in some places of a tubular sponge resembling the recent *Pallispongia vaginalis* in form, and growing in branched clusters to a height of about 20 centimeters. There was also a burrowing echinoderm fauna, of which examples of *Mellita sexiesperforata* and *Moira ? atropos* were found.

After the sandstone period, the area diverged into three types of ground—loose sand, beach, and mangrove swamp. In the loose sand, most of the sandstone species occur, together with many new additions. A few species disappeared, such as *Plicatula*, *Macrocallista*, *Chione*, *Lucina*, *Loripinus edentula* (this being replaced by *L. schrammi*), and the gastropod *Fasciolaria*. On the other hand five species of *Cymatium* occur for the first time as well as two more species of *Cypraea*, *Conus*, *Tonna*, *Strombus gigas*, two species of *Pecten*, *Ostrea virginica*, five species of *Tellina*, *Lima*, *Tagelus* etc. During this period *Chama congregata* was sometimes enormously abundant. One or two corals such as *Meandra* and *Agaricia* also occur for the first time, and at times *Oculina* spp. were extremely abundant. Unfortunately we have not sufficient data on the present fauna of the area to say with certainty which species

no longer occur there, but we have never seen a live *Cypraea*, *Cymatium*, or *Charonia*, or any species of *Strombus* other than *S. gigas*. Nor have we ever taken live *Meandrina*, *Montastraea*, or *Dichocoenia*. At the present time the area is mostly rather bare sand, and before the dredging commenced this was interspersed with extensive reefs which were mainly *Meandra* spp.

Mangrove swamps seem to have appeared in both Castle Harbour and Ferry Reach, although only in the latter have the deposits been transformed into rock. Such swamps still existed before the commencement of dredging operations, although less extensively than they must once have done. The fauna of the mangrove swamp deposits, as shown by the mangrove peat, *Isognomon* clay, and *Isognomon* rock, showed the mangrove oyster *Isognomon alata* to have been very abundant, presumably growing on the mangrove roots, together in places with considerable numbers of the gastropod *Lampanella minima*. This relationship is quite typical of present-day swamps.

The beach rock, as typified by *Brachydontes* rock, was characterized mainly by the two littoral forms *Brachydontes exustus* and *Lampanella minima* but contained some *Isognomon* and the following forms, most of which had probably washed in from deeper water: *Diadora* sp., *Ostrea frons*, *Plicatula plicata*, *Arca candida*, *Chama macrophylla*, *Lucina pensyllvanica*, *Codakia costata*, *C. orbicularis*, *Cerithium littoratum*, and the large tubular sponge referred to in the sandstone fauna. The presence of *Plicatula*, which was not found in the loose sand, suggests that this is a fairly early deposit, perhaps contemporary with the Castle Harbour sandstone.

SUMMARY

During the course of dredging operations in and around Castle Harbour, Bermuda, rock from fossil-bearing strata was obtained which can be interpreted to represent a series of beds about 40 feet thick. These beds appear to fill in the marine history of Bermuda between the post-volcanic period and the formation of the eolianites in the glacial period. It is recognized, however, that the beds may represent a period of rising sea level within the glacial period. An account is given of the species found and of their distribution in the different strata. The light which this sequence of beds and faunas throws on the early history of Bermuda is discussed, and it is concluded that the beds largely represent a period of shallowing of the sea. Finally a general picture of the local ecological conditions of each successive fauna is given.

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Manuscript Received by the Secretary of the Society, June 11, 1945.

OFFICIAL CALENDAR

March 15	Final spring date for filing applications for grants
March 27–29	Am. Geophys. Union meeting, George Washington University, Washington, D. C.
March 27–30	A. A. A. S. meeting, Municipal Auditorium, St. Louis
April 1–4	A. A. P. G. meeting, The Stevens, Chicago
April 13	Meetings, committees on Publications and Projects, New York
April 19–20	Cordilleran Section meeting, University of California, Berkeley
April 27	Council meeting, New York